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THERMAL ANALYSIS OF M552 EXPERIMENT FOR MATERIALS PROCESSING IN SPACE

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16. ABSTRACT

Analytical and experimental studies were made of heat flow in the exothermic brazing unit in the M552 experiment. The emphasis of the studies was placed on heat flow in the tube and the sleeve, especially during a period from ignition to the time when the brazing alloy solidifies.

Experiments were made of three specimens tested in a ground-base laboratory. Heat flow was determined by thermocouples.

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

SUMMARY

Analytical and experimental studies were made of heat flow in the exothermic brazing unit in the M552 experiment. The emphasis of the studies was placed on heat flow in the tube and the sleeve, especially during a period from ignition to the time when the brazing alloy solidifies.

Experiments were made of three specimens tested in a ground-base laboratory. Heat flow was determined by thermocouples.

The analytical study covered two phases. The first phase was to examine how reduced gravity could affect heat flow in the exothermic brazing unit. Among the three basic modes of heat transfer, i.e., conduction, convection, and radiation, convection is the only possible mode on which gravity has some effects. It was concluded that as far as the heat flow in the sleeve and portions of the tube surrounded by the sleeve during the period from ignition to the time when brazing alloy solidifies is concerned, the major mode of heat transfer is conduction and gravity has very little effect. Consequently, analytical models developed in their study only consider conduction. It should be pointed out, however, that gravity could have some effects on the transient heat flow during a very short period when the brazing alloy melts, spreads, and solidifies. No further study was conducted on this subject because of lack of basic information needed.

The second phase of analysis was to develop analytical models for heat flow in the exothermic unit. Analytical models were developed by use of the general-purpose, three-dimensional, finite-element heat flow program developed for the M551 experiment. Good agreements were obtained between experimental and analytical results indicating the soundness of the analytical models

SECTION I: INTRODUCTION

The objective of the M552 experiment is to study exothermic brazing of stainless steel tubes.

The study covered the following three phases:

Phase A: Preparation of ground base study plan
Phase B: Laboratory test program
Phase C: Experiment analysis program

During the above phases, M.I.T. efforts were made to provide the information on heat flow in brazing units to other contractors. For the heat flow analysis, the finite element computer program was developed by M.I.T.

To improve the analytical model which was used in the computer program, three ground-base experiments were conducted at M.I.T. by use of specimens which were sent by M.S.F.C. The experimental results obtained were compared with the analytical ones. By these efforts, data on the following problems were obtained analytically.

1. Temperature distribution in the tube and the sleeve
2. Rate of heat supplied to the sleeve from the exotherm material
3. Temperature distribution in the outer shell and the end washer

On the first subject, the temperature distributions on the inside wall of the tube and the sleeve were also obtained experimentally. On the second subject, the rate of heat supplied to the sleeve was estimated by comparing the temperature distribution of the inner wall of the tube obtained by the analysis with that obtained by the experiment. The third subject concerns heat flow from the exothermic brazing unit to the container. The experimental data on the outer shell were also obtained.

SECTION II: M.I.T. EFFORTS

M.I.T. efforts on the M552 experiment have been made, as illustrated in Figure 1. During phase A, all possible variables involved in the experiment were discussed. The heat flow analysis seemed to be very complex. However, a unique feature of heat flow analysis was that the effects of gravity appeared to be rather subtle. Gravity has no effect on heat conduction and radiation, therefore, convection is the only possible mode of heat transfer in which gravity has some effects. The most important subject in the heat flow analysis was concluded to be the information on the temperature distribution of the sleeve and the tube. Under the circumstances, the unknown factors in the M552 experiment were reduced to estimate the heat supplied to the outer wall of the sleeve.

The improvement of analytical models followed steps shown in Figure 1.

The experiment on three specimens were conducted at M.I.T. at the same time. The experimental results were used to improve the analytical model. After obtaining the reasonable heat supplied to the sleeve, the outer shell and the end washer, which were part of the package of the exotherm brazing unit were considered in the analytical model.

SECTION III: EXPERIMENTAL STUDY

A. GENERAL DESCRIPTION

During phase B, five brazing units and three exothermic modules were sent to M.I.T. from the G. C. Marshall Space Flight Center. Experiments were conducted on three specimens of the brazing unit. The objective of the experiments was to obtain the temperature distribution in a brazing unit and also to estimate the heat supplied to the outer wall of the sleeve. The estimated heat was used in the heat flow analysis of a model which was obtained by idealizing the actual brazing unit.

The experiments conducted are summarized in this report. Further information on the experiments are presented in References (1) to (3).

The experiments were performed with the assistance of Mr. Jay W. Spearman, a graduate student of the Department of Ocean Engineering; Mr. A. J. Zona of the Department of Metallurgy and Materials Science; and Mr. Fred Merlis of the Department of Aeronautics and Astronautics.

B. EXOTHERMIC BRAZING UNIT

Figure 2 shows the exothermic brazing unit used in the experiments. The tubular joint which is concerned with the clearance between the sleeve and the tube is reproduced as Figure 3. The tube was 0.75 inches in outer diameter, 0.049 inches in wall thickness and 3.6875 inches in length. The materials of the sleeve and the tube were fabricated from 347 stainless steel, while brazing alloy was AWS A5.8-62 Class B Ag-8a filler material (71.8% Ag, 28% Cu, and 0.2% Li).

The heat required to melt or flow a brazing filler metal is generated by the exothermic reactant mixture which consisted of metals and metal oxides. When matched to the heat sink characteristics of the tubing, sixty grams of this exothermic material produces 650 $\pm$ 30 calories/gram.

Application of 24 volts d.c. current to the igniter leads heats the tungsten filament in the igniter pyrotechnic material sufficiently to cause combustion.

The heat generated from this reaction in turn, ignites the primary exothermic charge. This heat transferred through the coupling of the sleeve and the tube liquifies the two concentric rings of brazing alloy. The alloy then flows the length of the brazing alloy cavity until it is contained by the interference fit at the ends of coupling.

C. EXPERIMENTAL APPARATUS

A description of the thermocouple instrumentation circuit is shown in Figure 4. Chromel-alumel thermocouples spot-welded onto the specimen were used in the experiments. A Honewell visicorder was used to monitor the thermocouples. Ignition of exothermic material was accomplished by applying 28V DC, 150 Amp. from the welding machine.

D. DESCRIPTION OF EXPERIMENTS

As shown in Figure 5, experiments were conducted on three specimens. Each experiment is described as follows:

1. Experiment 1

a. The objective of this experiment was considered to be a preliminary one.

b. The temperature distribution of the inner wall of the tube was studied.

c. Eight thermocouples were set on the inner wall of the tube: four per side, with one set on the top and the other set on the bottom (see Figure 5).

d. The specimen was enclosed in a plexiglas box which was purged with an argon atmosphere.

e. Data were recorded for about forty-seven minutes.

f. The maximum temperature observed after forty-seven minutes from ignition was 170°F above room temperature (73°F) at thermocouple #5 shown in Figure 5.

g. The observed time-temperature change curves for eight thermocouples are shown in Figures 6 and 7.

2. Experiment 2

a. The objective of this experiment was to measure the temperature distribution of the inner wall of the tube and to obtain the reliable data for estimating supplied heat to the outer wall of the sleeve.

b. The laboratory set-ups for the experiment are shown in Photograph 1.

c. The specimen was enclosed in a plexiglas box which was purged with argon atmosphere (see Photograph 2).

d. Eight thermocouples were used, seven of which were arranged on the one side from the center and along the inner wall of the tube. The eighth thermocouple was located on the top of the outer shell of the brazing unit (see Figure 5).

e. Data were recorded for thirty-five minutes.

f. During the experiment, thermocouple 2 failed.

g. The tube wall temperature changes from room temperature were still above 250^{o}F and the outer shell temperature, over 100^{o}F after thirty-five minutes from ignition. Room temperature was 73^{o}F during the experiment.

h. The observed time-temperature change curves are shown in Figures 8 and 9.

3. Experiment 3

a. The objective of this experiment was to obtain the data on heat supplied to the sleeve to improve the distribution and the history of heat used in the analysis.

b. The laboratory set-up is shown in Photograph 3.

c. The specimen was set on a brick on the circular disc and covered with a cylindrical capsule made of steel (see Photograph 4).

d. The inside of the capsule was under the pressure of 270×10^{-3} mm Hg. at the beginning of the experiment.

e. Eight thermocouples were arranged, three of which were on the outer shell of the exotherm heater assembly and th rest of which were on the inner wall of the sleeve (see Figure 5).

f. Thermocouple 1 was set just on the brazing alloy.

g. Data were recorded for 45 minutes.

h. Room temperature was 75^{o}F during the experiment.

i. The observed time-temperature change curves are shown in Figures 10 to 13.

j. The appearance of melting of the brazing alloy after the experiment is shown in Photograph 5.

E. SUMMARY OF EXPERIMENTAL OBSERVATIONS

Important findings obtained through experiments are as follows.

1. The maximum temperature of the inner wall of the tube is between 1900° and $2000^{\circ}F$.
2. The center of the tube is nearly the hottest point.
3. The temperature distribution of the inner wall of the tube is almost symmetric for the middle point of the tube length.
4. The temperature distribution is almost axisymmetric.
5. The maximum temperature of the shell is between 600° and $800^{\circ}F$.
6. The center of the inner wall of the tube starts cooling down around 60 seconds from ignition.
7. Temperature of the brazing alloy cools down below the melting point ($1400^{\circ}F$) after about 240 seconds from ignition.

The above findings gave a basis to simplify analytical models. The assumptions adopted in simplifying the models are described in the following pages.

SECTION IV: DEVELOPMENT OF ANALYSIS

A. EFFECTS OF REDUCED GRAVITY ON HEAT FLOW IN THE EXOTHERMIC BRAZING UNIT

First, a study was made to examine how reduced gravity could affect heat flow in the exothermic brazing unit, especially heat flow in the tube and the sleeve during a period from ignition to the time when the brazing alloy solidifies. Heat is transferred in basically three modes: conduction, convection, and radiation. Gravity has no effect on conduction and radiation, and convection is the only mode of heat transfer in which gravity can have some effects.

By examining the design of the exothermic brazing unit and experimental data, one can easily conclude that the principal mode of heat transfer in the tube and sleeve during the above-mentioned period is conduction. However, heat transfer due to convection occurs in the following regions (refer to Figure 14):

a. In an atmosphere surrounding the sample
b. In the molten brazing alloy
c. In the gap between the sleeve and the tube
d. In an atmosphere inside the shell which contains the exothermic units.

Since the exothermic experiments in the Skylab were conducted in a vacuum chamber, heat loss in convection to the surrounding atmosphere (Item a) is very lettle, if any. Heat loss in convection can occur in the ground-base experiments done in an argon atmosphere. However, the effects are pronounced in regions exposed to the atmosphere during later stages of an experiment when the entire specimen cools. Consequently, effect of Item a can be neglected.

Items b and c can have some effects on solidification patterns of the brazing alloys. While the molten brazing alloy spreads along the gap between the sleeve and the tube, some heat is transferred in convection and gravity can produce some effects. Heat also is transferred in convection in the atmosphere which fills the gap between the sleeve and the tube. These heats may cause some effects on solidification patterns of the brazed alloy. However, these effects are very difficult to determine quantitatively because the gap is very narrow (0.005 to 0.030 inch) and the braze alloy spreads rather rapidly. The effects could not be detected by measuring temperature changes of thermocouples placed in the inside wall of the tube.

The effect of Item d is believed to be negligible because the shell contains exothermic units and insulation materials and there is little open space in the shell.

After these analyses, it was concluded that as far as the heat flow in the sleeve and portions of the tube surrounded by the sleeve during the period from ignition to the time when the brazing alloy solidifies is concerned, the major mode of heat transfer is conduction and gravity has very little effect. Consequently, analytical models developed in this study, which will be discussed in the following pages, consider conduction only.

It is noted that gravity could have some effects on the transient heat flow during a very short period when the brazing alloy melts, spreads and solidifies, as discussed above. However, no further study was conducted on this subject because of lack of basic information needed.

B. BASIS FOR DEVELOPING ANALYTICAL MODELS

In the analysis of heat flow in the M552 experiment, the following questions need to be answered:

a. How much heat is produced by the exotherm material?

b. What are the rate and the distribution of heat supplied to materials which surround the exotherm material?

c. What are the thermophysical properties of the material used for insulation?

d. How much effect does radiation have upon the temperature distribution of the unit?

e. How does the gap between the sleeve and the tube work in conveying heat?

f. How much effect do melting and solidification of the brazing alloy have upon the temperature distribution of the sleeve and the tube?

During the heat flow analysis of the M551 experiment, a general-purpose, three-dimensional, finite-element program was developed. It was decided to develop analytical models for heat flow during exothermic brazing by use of the above computer program.

Although the program itself can analyze quite a variety of problems, efforts were made to develop analytical models complex enough to provide accurate results but not unnecessary complex. First, a very simple model was used, and analytical and experimental results were compared. Then more complex models were developed to improve accuracy. However, on the basis of the experimental data, the following assumptions were made throughout the analysis:

a. The temperature distribution of the specimen is axisymmetric.

b. The temperature distribution of the specimen is symmetric for the middle point of the tube length.

c. The gap between the sleeve and the tube is ignored.

d. The problems concerning heat generated by the exothermic material are reduced to that of estimating the heat supplied to the outer wall of the sleeve.

e. The melting and the solidification of the brazing alloy are not considered.

f. Radiation is neglected.

Assumption c is also related to the discussions on the effect of gravity described in the preceding section. Radiation between the sleeve and the tube will work very effectively because of the narrow gap. Therefore the temperature of the outer wall of the tube facing the inner wall of the sleeve reaches almost the same temperature as that of the sleeve in a small time lag. Therefore this gives another validity to assumption c. Various unknown factors on the heat generated by the exothermic material were simplified and introduced into the analysis by assumption d. The brazing alloy melts, spreads, and solidifies in the gap between the sleeve and the tube. These effects are very difficult to determine quantitatively and to consider in the analysis. However these effects will be little on the heat flow in the sleeve and the sleeve, if any, because the gap is very narrow. Assumption c is based on this reason. Assumption e is also related to c.

The heat flow in the sleeve and portions of the tube surrounded by the sleeve during the period from ignition to the time when the brazing alloy solidifies is not affected by heat emission due to radiation from the outer walls of the shell and the end washer. For the above reason, Assumption f was adopted.

The questions listed at the beginning of this section were, therefore, answered in the discussions on the assumptions made for the analysis.

Finally, the analysis was made for 120 seconds from ignition, which is most important for the study of melting and spreading of the brazing alloy.

C. THE INITIAL STUDY

In the first model, the distribution of heat supplied to the outer wall of the sleeve was assumed to be type C, which was uniform heat intensity as shown in Figure 15. The heat was also assumed to be supplied constantly and to disappear at 57 seconds from ignition. In the second model, the heat was assumed to be still unifirmly distributed, but to change the intensity with time. The analytical results had some discrepancy at the center and also at the end of the tube. The results were given in the reports presented earlier (see References (1), (2), and (3)). Improvement of the analytical results were achieved in models described in the following pages.

D. THE PROGRESSIVE STUDY

The progressive study consists of two parts. The first is to make further improvements on the model of heat supplied to the sleeve. The second part is to take into account the outer shell and the end washer into the analysis.

1. First Progressive Study. In the third model, the heat intensity is assumed to change with time and the combination of types A, B, and C is used to represent the distribution of heat source, as shown in Figure 15. The difference between the intensities of heat distributed along the sleeve is 20% compared with the value marked by q shown in Figure 15. The figure also shows the mesh pattern used for the finite element analysis. The following values are adopted as thermophysical properties of 347 stainless steel.

Specific heat	=	0.12 Btu/lb/^{o}F
Thermal Conductivity	=	0.278×10^{-3} Btu/sec/inch/^{o}F
Density	=	0.29 lb/inch^{3}

The analytical results are given in Figures 16 to 19. Figures 16 to 18 show the comparisons between experimental and analytical results. Figure 19 shows the temperature distribution of the joint of the sleeve and the tube at times 30, 40, 60, and 120 seconds.

From figures 16 to 18, it is seen that the analysis is improved. However, it is also seen that the analytical results still do not agree well with the experimental one at thermocouple 7 which is located almost at the end of the tube.

Discussions on this discrepancy will be made after results obtained by the second progressive study are shown.

In determining the intensity of heat, a different manner from that of the initial study is taken. This is written simply as follows:

The calculated temperature at thermocouple 1 in the second experiment at 50 seconds

=

The observed temperature at the same location and at the same time

2. Second Progressive Study. As seen in Figure 20, Model 4 includes the outer shell and the end washer to study the temperature distribution of those portions analytically. The heat intensity is assumed to change with time as shown in Figure 21.

For representing the distribution of heat source type c is used by combining with type a. The mesh pattern for the analysis is shown in Figure 20. The same thermophysical properties mentioned above are adopted for the whole finite element model.

Figures 22 to 25 show the comparisons between the experimental and the analytical results at thermocouples 1, 4, 7, and 8 in the second experiment. The analytical results are not necessarily improved as compared with those obtained without considering the outer shell and the end washer. This probably comes from the assumption that the radiation is not considered. Figures 24 and 25 which represent temperatures at the outer surface of the specimen seem to show the effect of radiation. In other words, further improvement of the analysis will be made by considering radiation.

SECTION V: BRIEF DESCRIPTION OF COMPUTER PROGRAM

During Phase B of the M551 experiment, a computer program based on the finite element method was developed at M.I.T. The computer program was modified to analyze an axisymmetrical body with axisymmetrical boundary conditions. The following items were considered in developing the computer program:

a. The program can be applied to a heat flow analysis of any axisymmetrical body.

b. Both specified temperature and supplied heat are treated as boundary conditions.

c. The non-stationary heat flow problem as well as the stationary one can be solved by the same program.

d. The program should be flexible for future improvement or modification.

These items were achieved by use of the finite element method. The finite element approach to the problem is given in the appendix. More details of the approach are described in Reference 4.

SECTION VI: CONCLUSION

Analytical and experimental studies were made of heat flow in the exothermic brazing unit in the M552 experiment.

Experiments were made of three specimens tested in a ground-base laboratory. Important findings obtained through the experiments are as follows:

1. The maximum temperature of the inner wall of the tube is between 1900^{o} and 2000^{o}F.
2. The center of the tube is nearly the hottest point.
3. The maximum temperature of the shell is between 600^{o} and 800^{o}F.

Effects of reduced gravity on heat transfer in the sample are little. Gravity could have some effects on convection which occurs in the gap between the sleeve and the tube during a very short period when the brazing alloy melts, spreads, and solidifies, if any. However, the major mode of heat transfer in the brazing unit is conduction.

On the basis of the experimental data and also the discussions on the effects of gravity on heat transfer, analytical models were developed for heat flow in the exothermic brazing unit. The finite element method was used to develop the models and the computer program based on the method was used extensively.

Good agreements were obtained between experimental and analytical results of the temperature distribution in the sleeve and portions of the tube surrounded by the sleeve.

SECTION VII: APPENDIX

A. SYMBOLS

A	area
C	specific heat
k	thermal conductivity
n_r, n_z	components of unit normal vector
$\dot{Q}$	rate of internal heat generation
T	temperature
$\bar{T}$	prescribed temperature
t	time
V	volume
r,z	position coordinates
ρ	density

B. BASIC THEORY

The basix matrix equation is derived for the finite element analysis of a heat flow problem. The specimen under consideration is axisymmetric in its configurations and boundary conditions. The most convenient coordinate system for the analysis of such a body is to define the axes coincident with the radial and axial coordinates, respectively. By using the coordinate system, the governing equation and the boundary conditions are given as follows:

$$k\frac{\partial T}{\partial r} + r\frac{\partial}{\partial r}\left(k\frac{\partial T}{\partial r}\right) + r\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) + \dot{Q} = C\rho\frac{\partial T}{\partial t} \text{ in } V \quad \text{(A-1)}$$

$$T = \bar{T} \text{ on } A_2 \quad \text{(A-2)}$$

$$kr\left(n_r\frac{\partial T}{\partial r} + n_z\frac{\partial T}{\partial z}\right) = 0 \text{ on } A_3 \quad \text{(A-3)}$$

where r and z denote the radial and the axial coordinates respectively.

Equation (A-3) means that the heat emission such as radiation is not considered in this analysis.

The principle of virtual work equivalent to equations (A-1) and (A-3) is obtained as follows:

$$\iint \left[k \left\{ \frac{\partial T}{\partial r} \delta \left(\frac{\partial T}{\partial r}\right) + \frac{\partial T}{\partial z} \delta \left(\frac{\partial T}{\partial z}\right) \right\} + C\rho\frac{\partial T}{\partial t} \delta T - \dot{Q}\delta T\right] rdrdz = 0 \tag{A-4}$$

In equation (A-4), temperature must satisfy boundary condition (A-2). In other words, equation (A-2) is the subsidiary condition for equation (A-4).

In addition, it is pointed out that equation (A-4) is derived under the assumption that $\frac{\partial T}{\partial t}$ and $\dot{Q}$ do not change while taking the variation δT.

Once the variational formulation of the problem is made, the approach to derive the matrix equation is straight-forward and made in a similar manner presented in Reference (4). Therefore, a trial function to represent temperature distribution approximately in an element and a brief comment on the final form of the matrix equation are given here.

As a basic finite element, a triangular element is adopted. The following trial function is used for the element.

$$T = \alpha_o + \alpha_1 r + \alpha_2 z \tag{A-5}$$

The matrix equation is obtained as follows:

$$[H]\{T\} + [P]\{\dot{T}\} - \{\dot{F}\} = \{0\} \tag{A-6}$$

where ($\dot{}$) denotes time derivative.

Each term in equation (A-6) comes from the corresponding terms of equation (A-4) as follows:

$$\iint k \left\{ \frac{\partial T}{\partial r} \delta \left(\frac{\partial T}{\partial r}\right) + \frac{\partial T}{\partial z} \delta \left(\frac{\partial T}{\partial z}\right)\right\} rdrdz \rightarrow [H]\{T\}$$

$$\iint C\rho\frac{\partial T}{\partial t} \delta T\, rdrdz \rightarrow [P]\{\dot{T}\}$$

$$\iint \dot{Q}\delta\, Trdrdz \rightarrow \{\dot{F}\}$$

By applying the finite difference method to the time coordinate, equation (A-6) eventually becomes as follows:

$$([H] + \frac{2}{\Delta t} [P])\, \Delta \{T\}_i = -2[H]\{T\}_{i-1} + \{F\}_{i-1} + \{F\}_i \tag{A-7}$$

where

$$\{T\}_i = \{T\}_i - \{T\}_{i-1}$$

and the subscripts i and i-1 denote times, t_i and t_{i-1}, respectively.

Equation (A-7) is the final matrix equation for the non-stationary heat flow analysis of the axisymmetrical problem. If initial conditions are given, equation (A-7) can be solved step-by-step at every time increment.

SECTION VIII: ACKNOWLEDGEMENT

The authors would like to thank Mr. Anthony Zona, Mr. Fred Merlis, and Mr. Jay Spearman for their assistance in carrying out these experiments.

SECTION IX: REFERENCES

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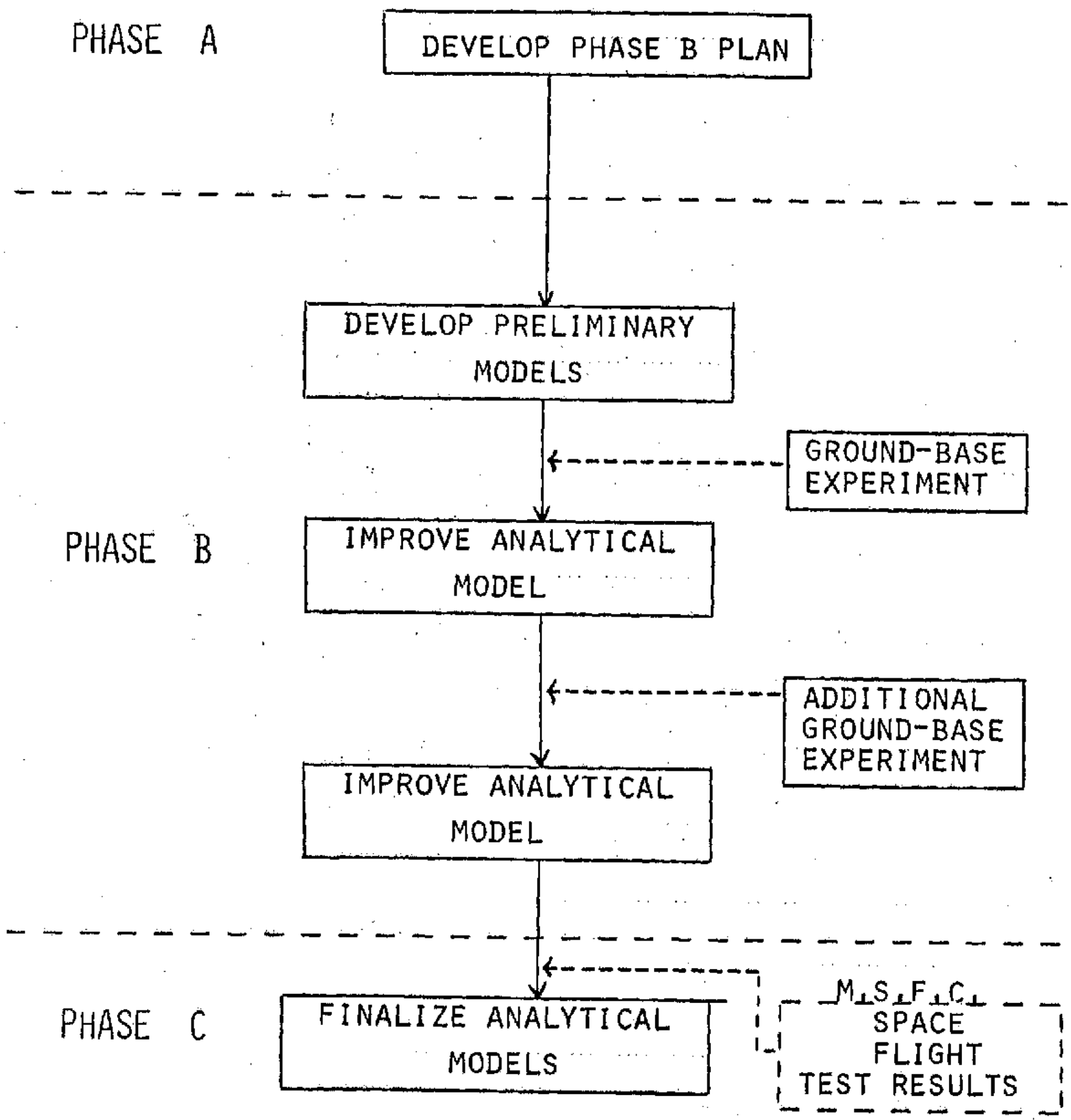


FIGURE 1 M.I.T. Efforts

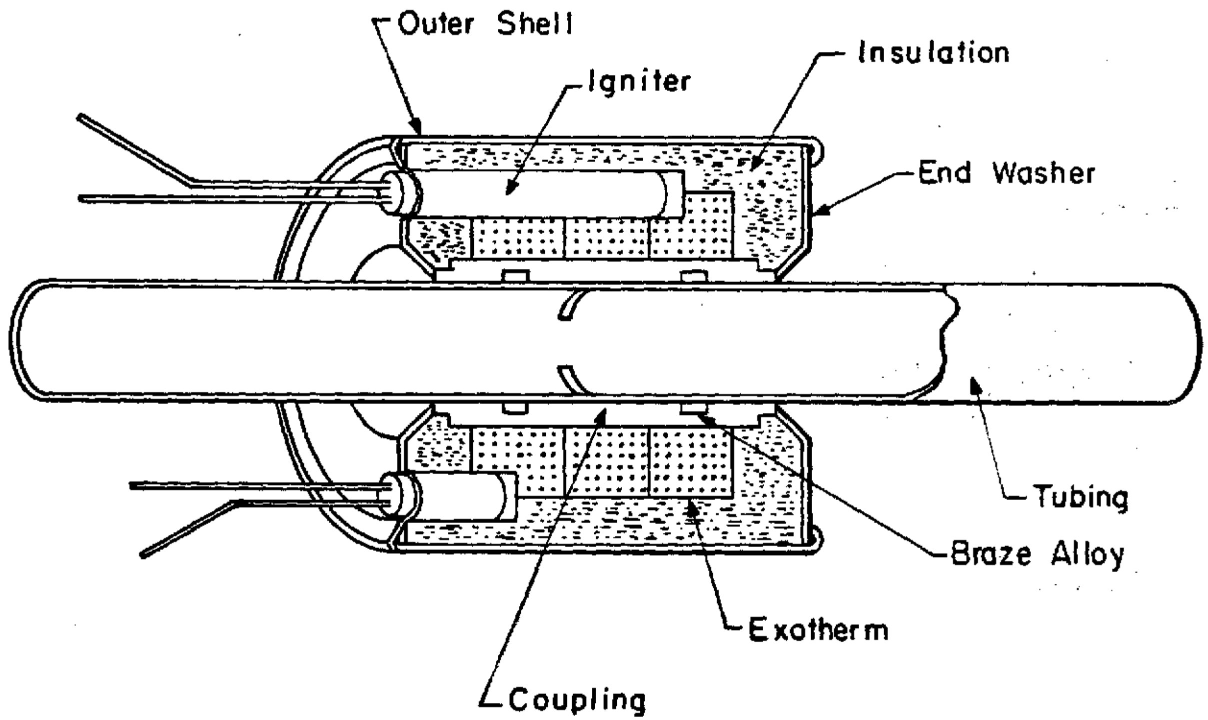


FIGURE 2 Cross Section of Exothermic Braze Unit

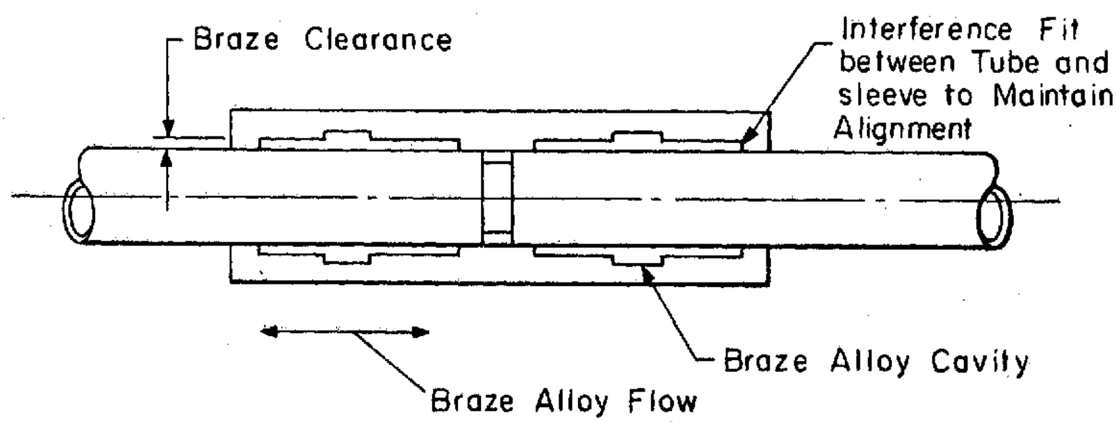


FIGURE 3 Concentric Braze Clearance Joints

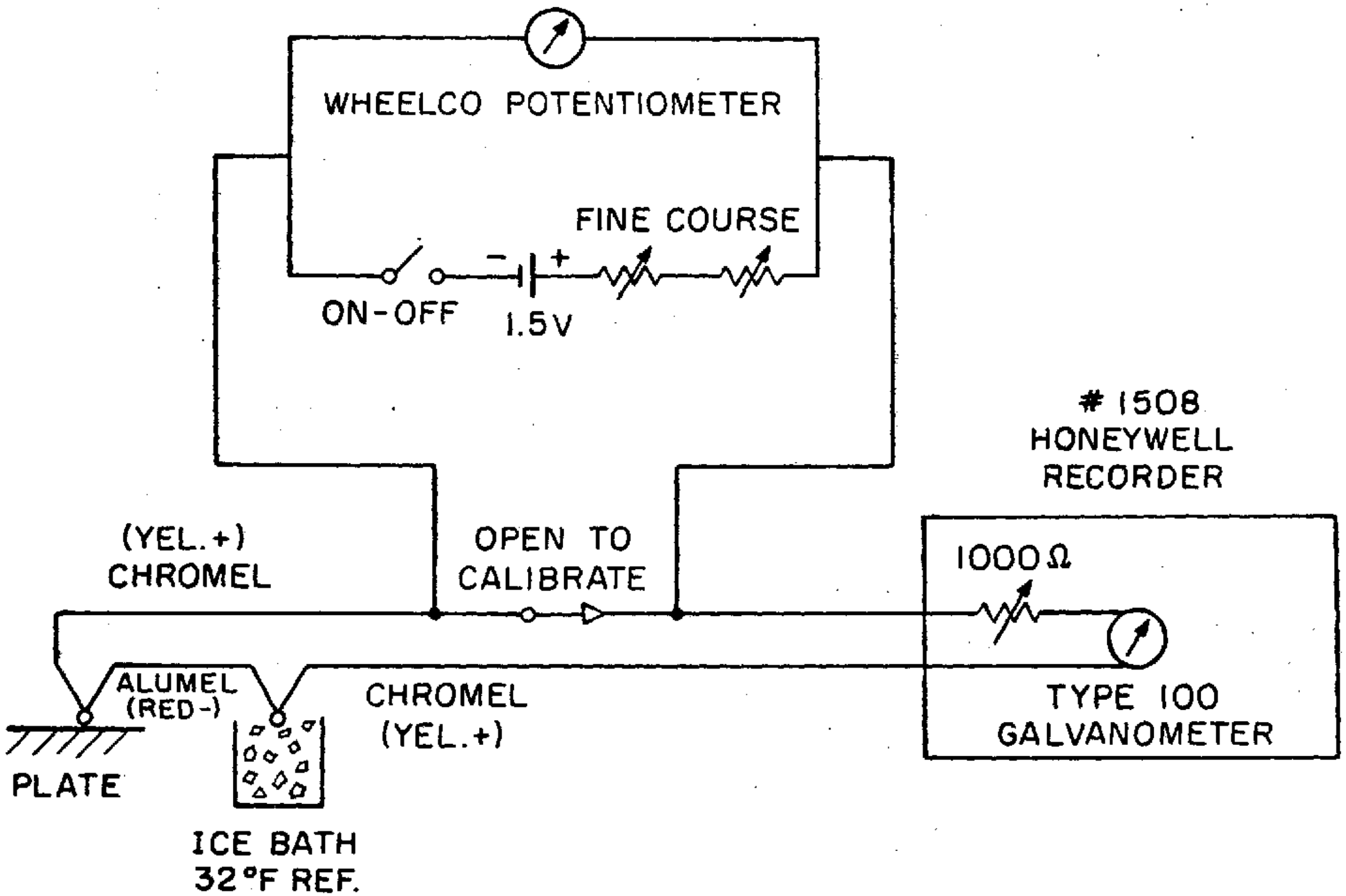
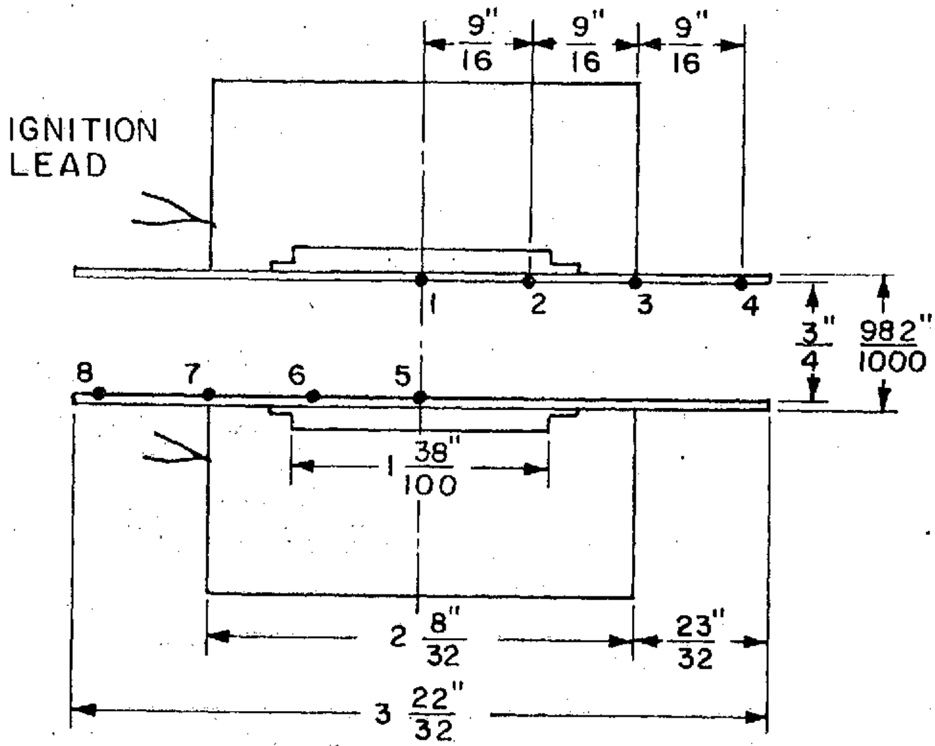
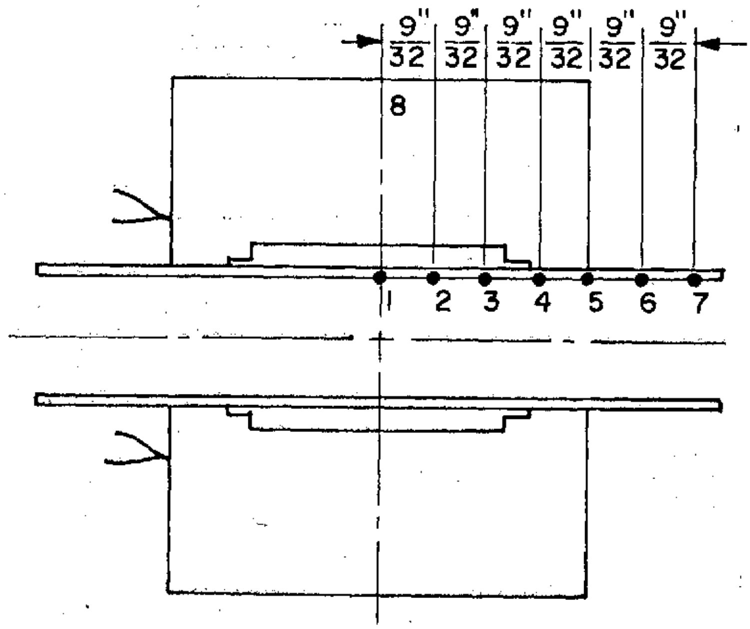


Figure 4 Thermocouple Instrumentation Circuit



EXPERIMENT 1



EXPERIMENT 2

FIGURE 5 Locations of Thermocouples in Specimens Tested

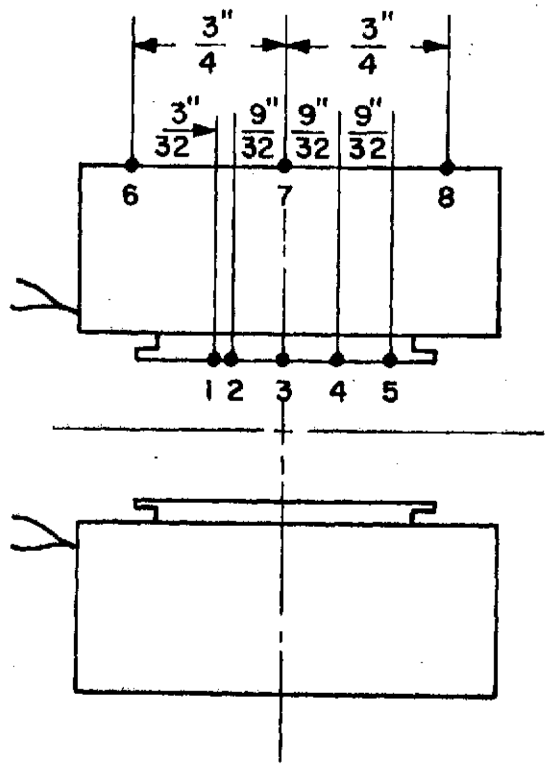
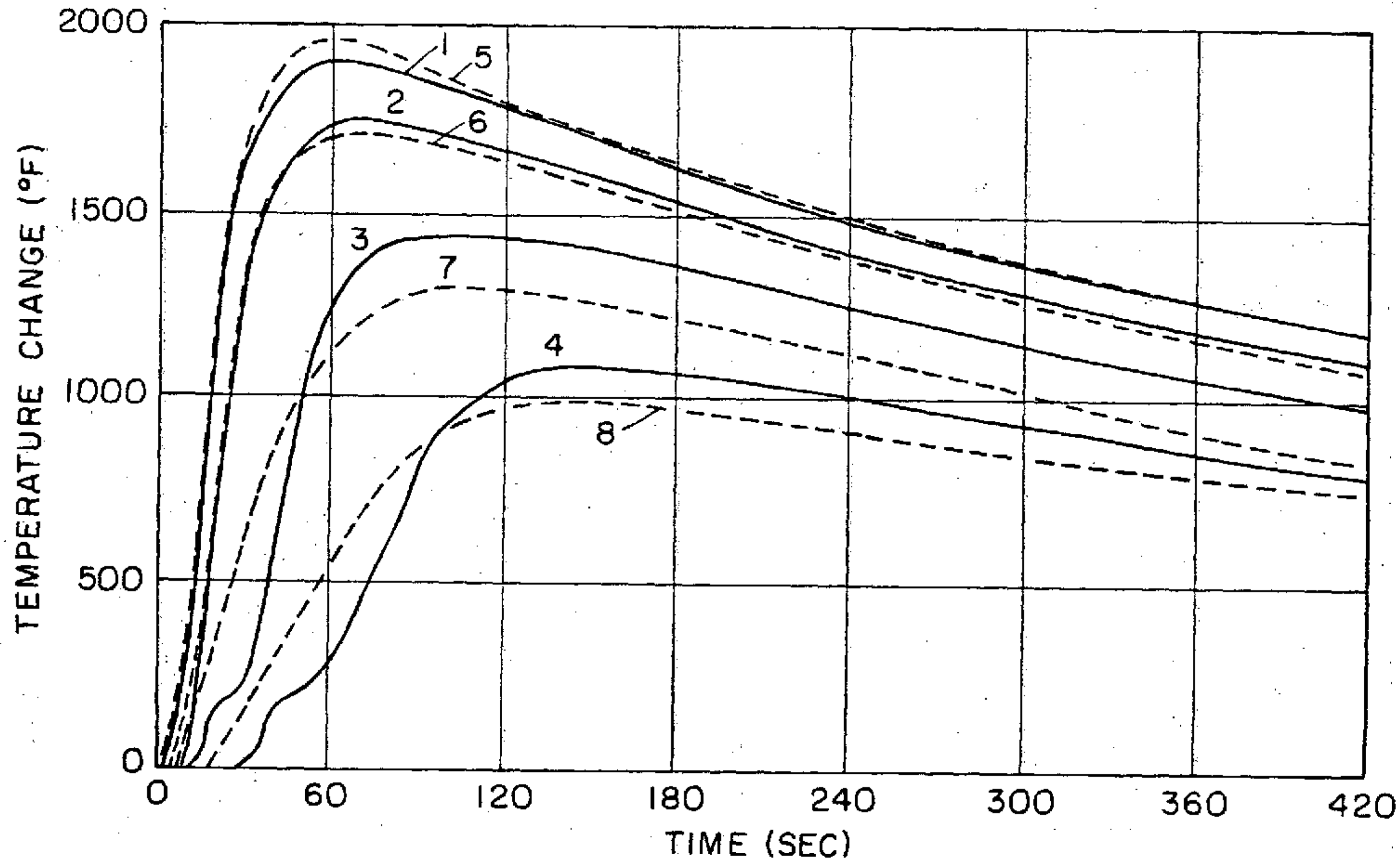
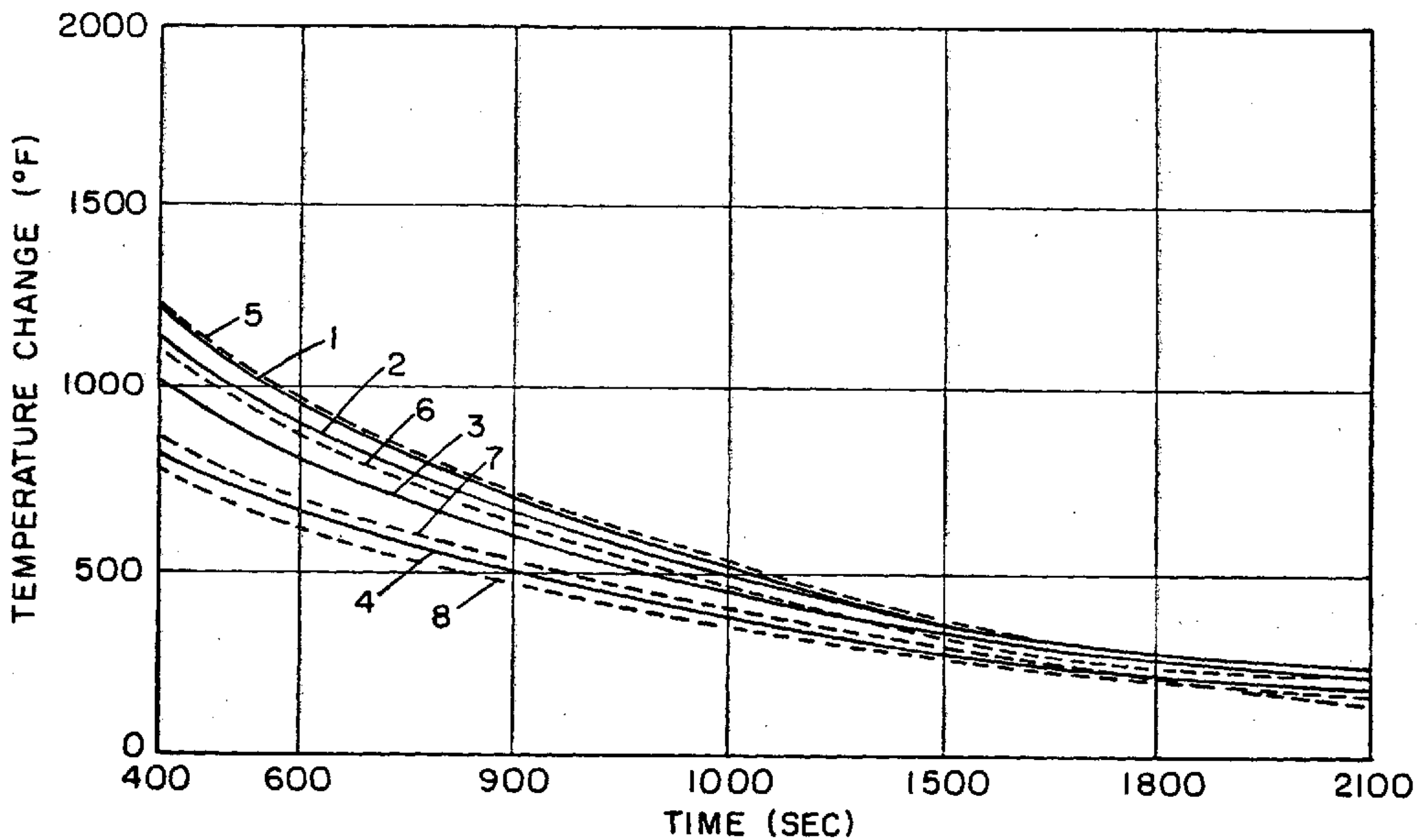


FIGURE 5 Locations of Thermocouples in Specimens Tested (cont.)



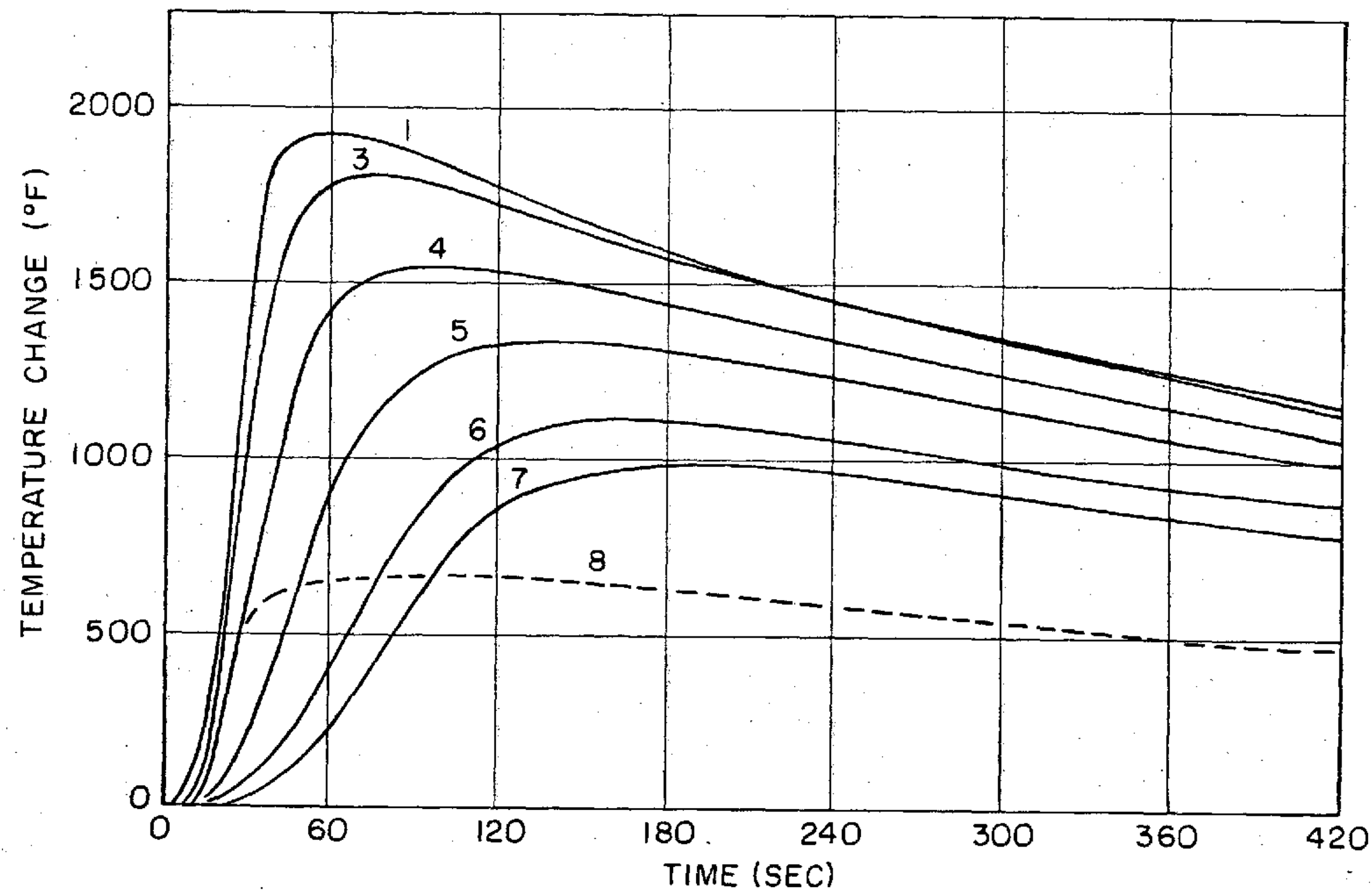
Note: Numbers on Curves Denote Thermocouple Numbers

FIGURE 6 Temperature Change Measured in Experiment 1



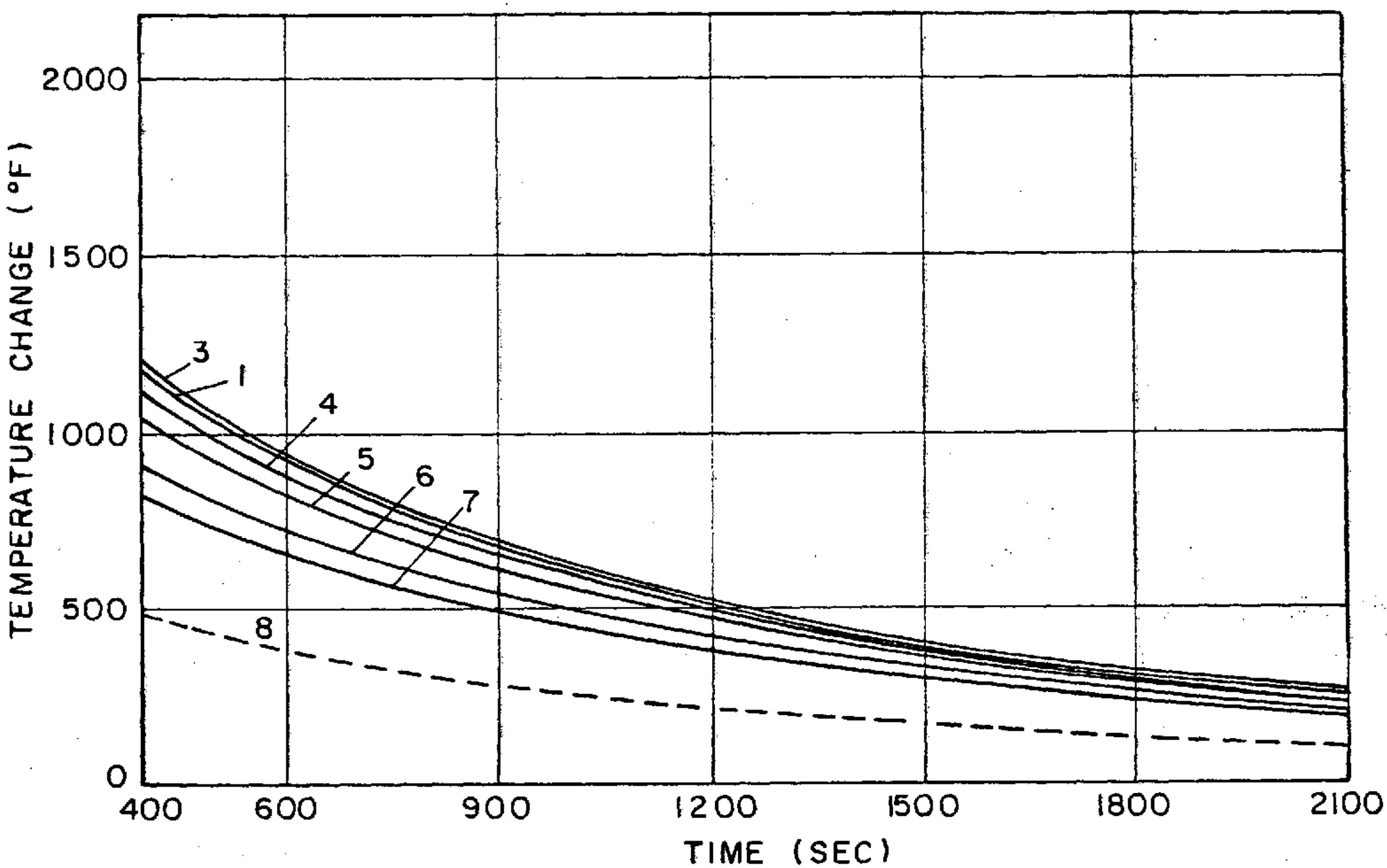
Note: Numbers on Curves Denote Thermocouple Numbers

FIGURE 7 Temperature Change Measured in Experiment 1



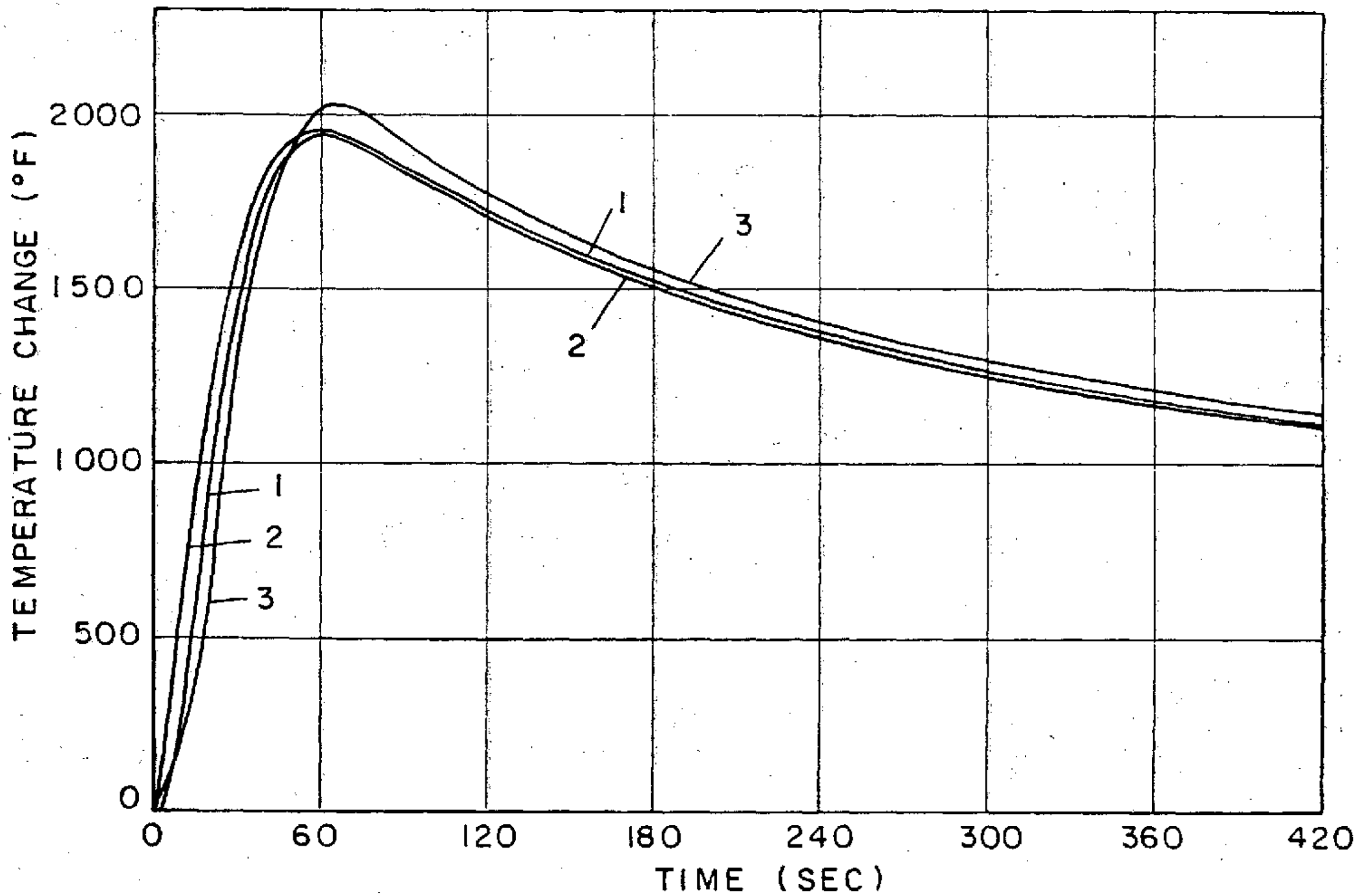
Note: Numbers on Curves Denote Thermocouple Numbers

FIGURE 8 Temperature Change Measured in Experiment 2



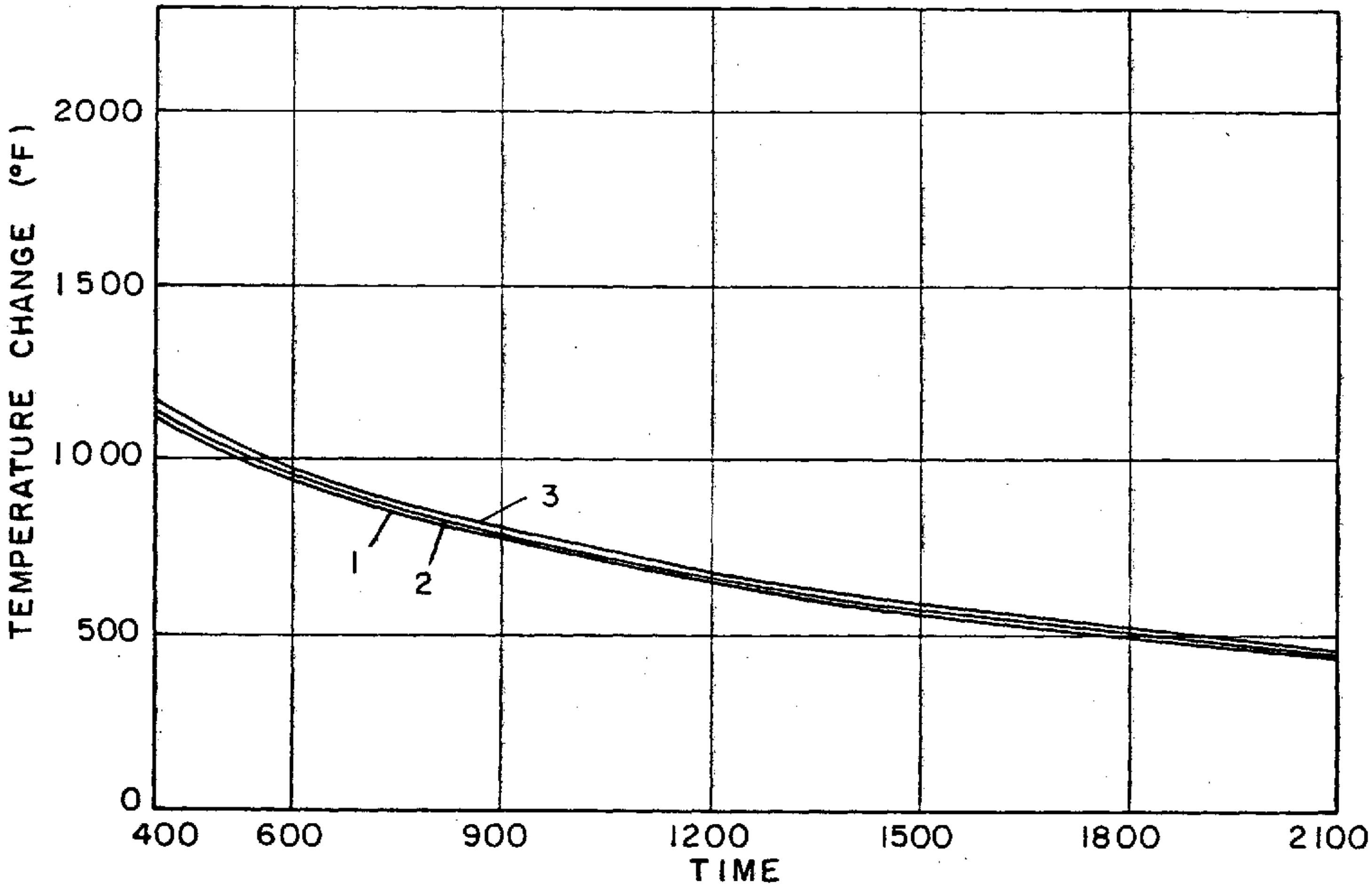
Note: Numbers on Curves Denote Thermocouple Numbers

FIGURE 9 Temperature Change Measured in Experiment 2



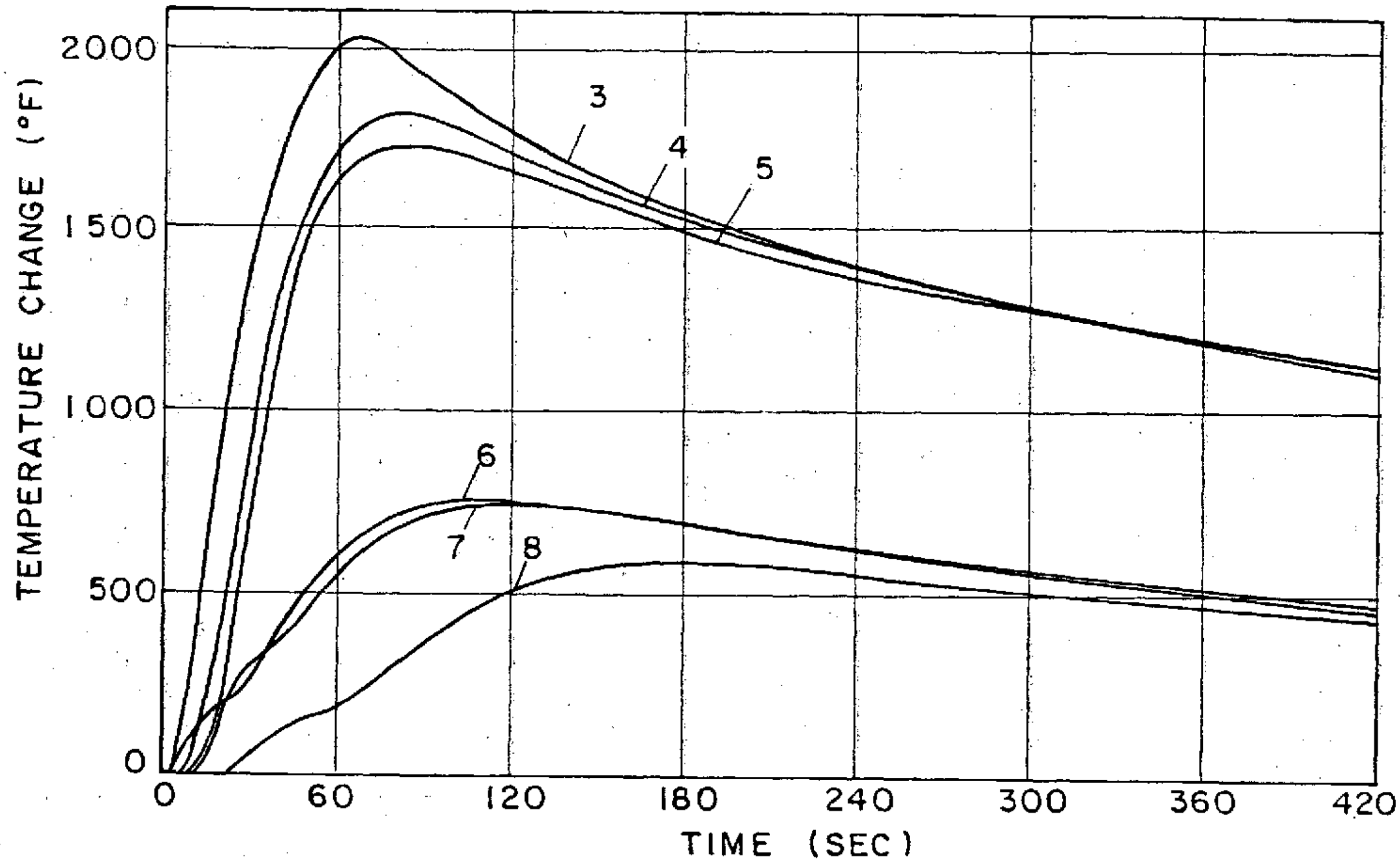
Note: Numbers on Curves Denote Thermocouple Numbers

FIGURE 10 Temperature Change Measured in Experiment 3



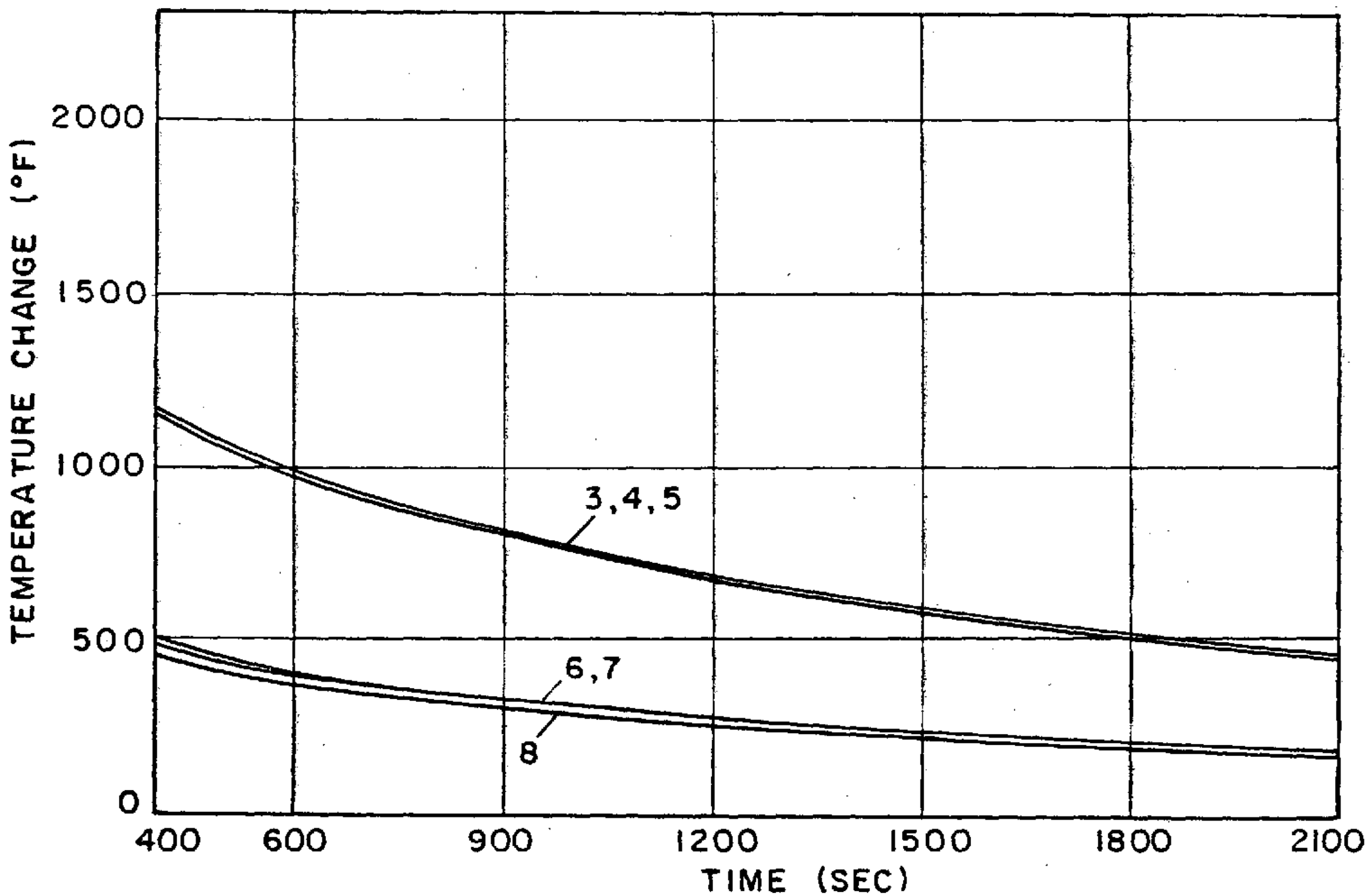
Note: Numbers on Curves Denote Thermocouple Numbers

FIGURE 11 Temperature Change Measured in Experiment 3



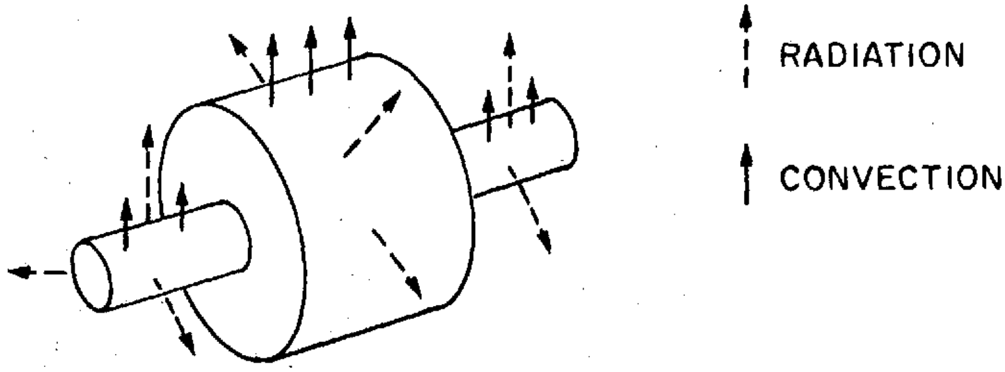
Note: Numbers on Curves Denote Thermocouple Numbers

FIGURE 12 Temperature Change Measured in Experiment 3

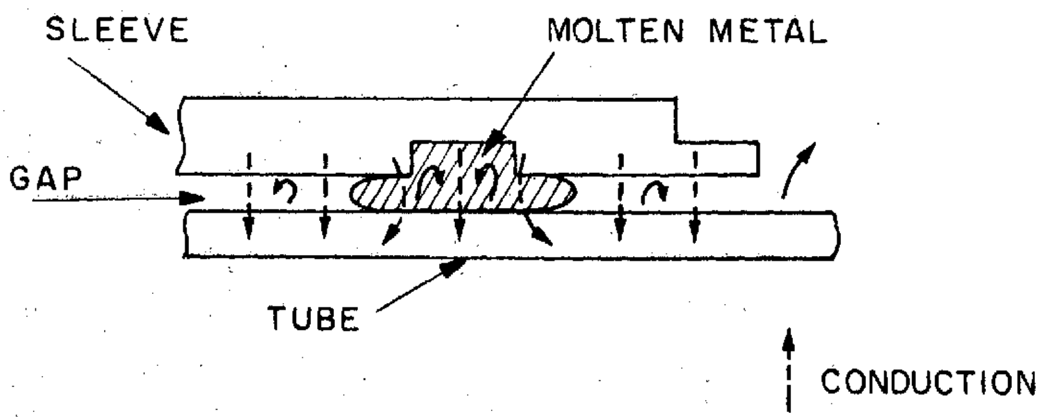


Note: Numbers on Curves Denote Thermocouple Numbers

FIGURE 13 Temperature Change Measured in Experiment 3

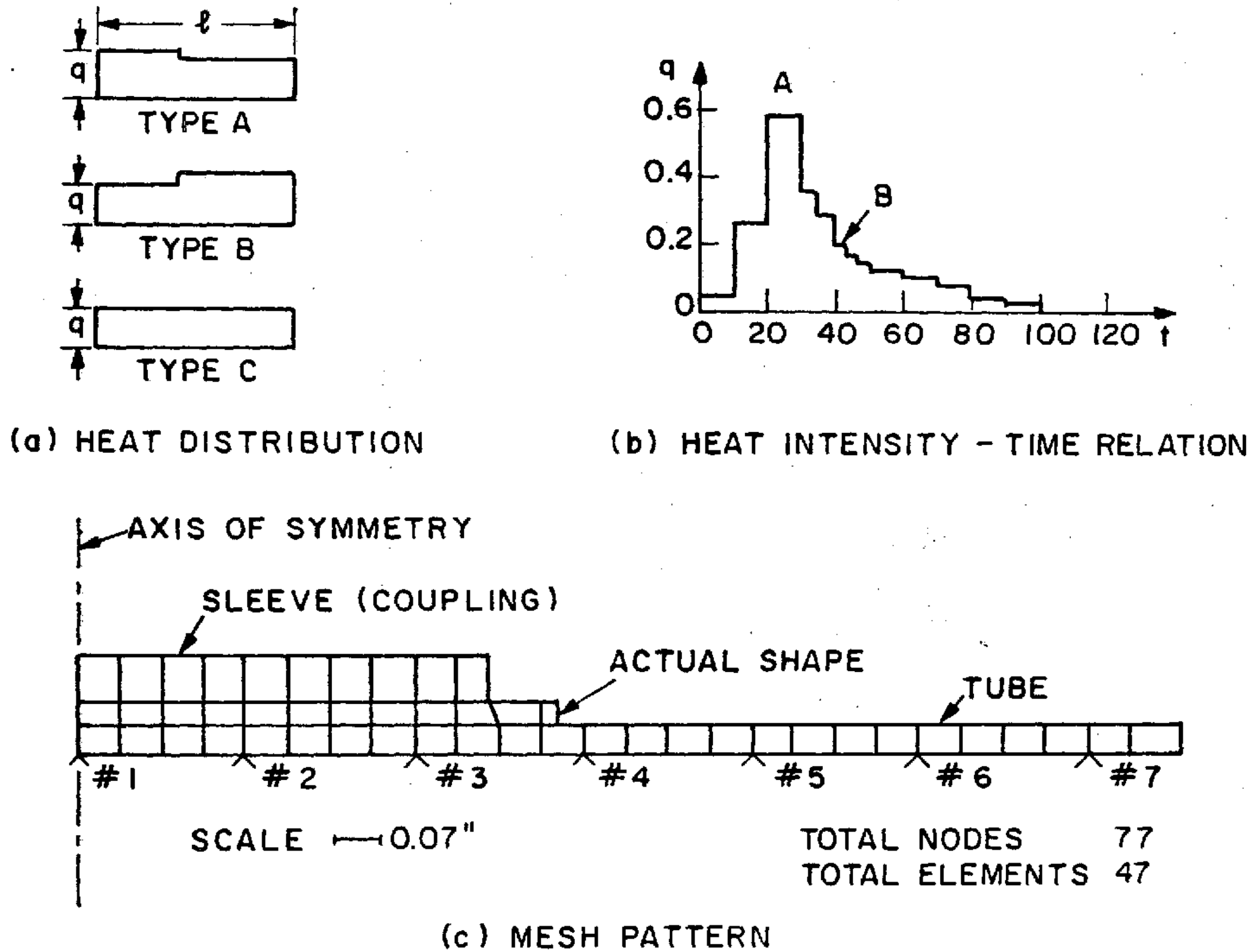


(a) Brazing Unit



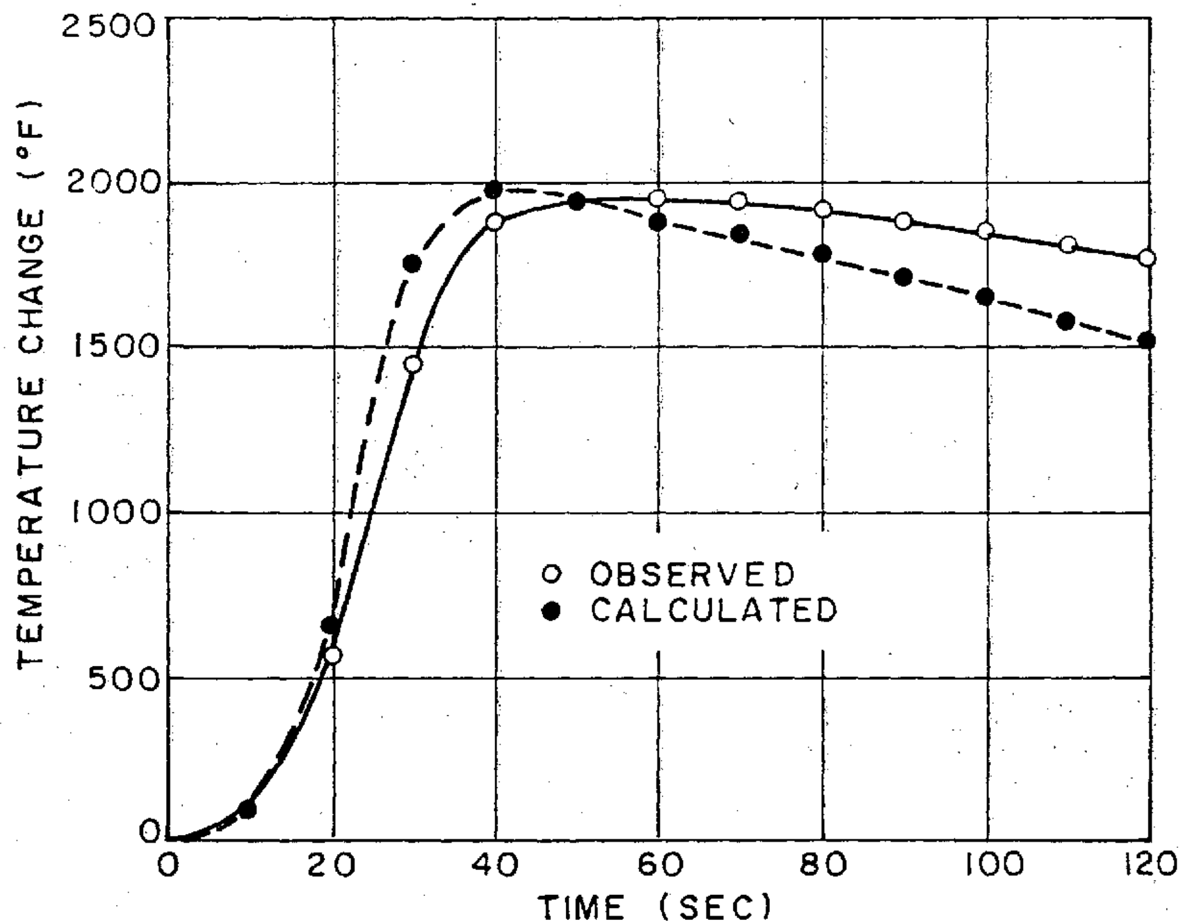
(b) Gap between Sleeve and Tube

FIGURE 14 Heat Transfer Modes



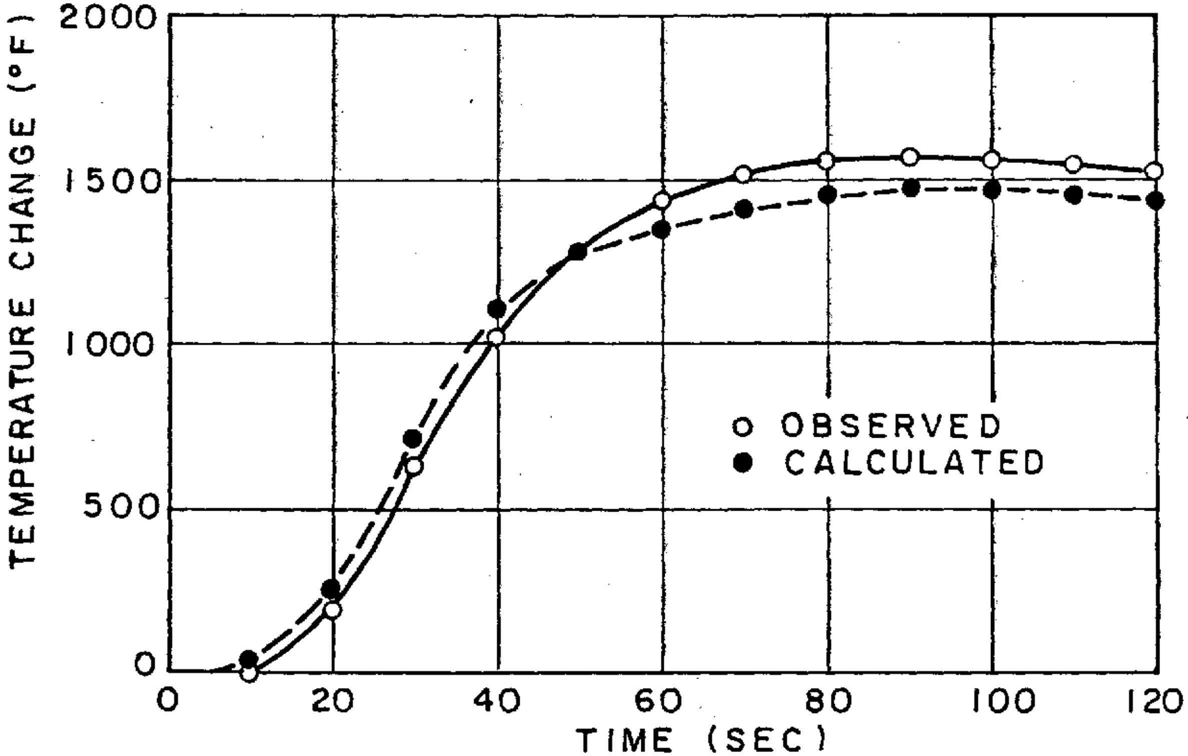
Note: #1 to #7 Denote the Locations of Thermocouples Used in Specimen No. 2

FIGURE 15 Analytical Model



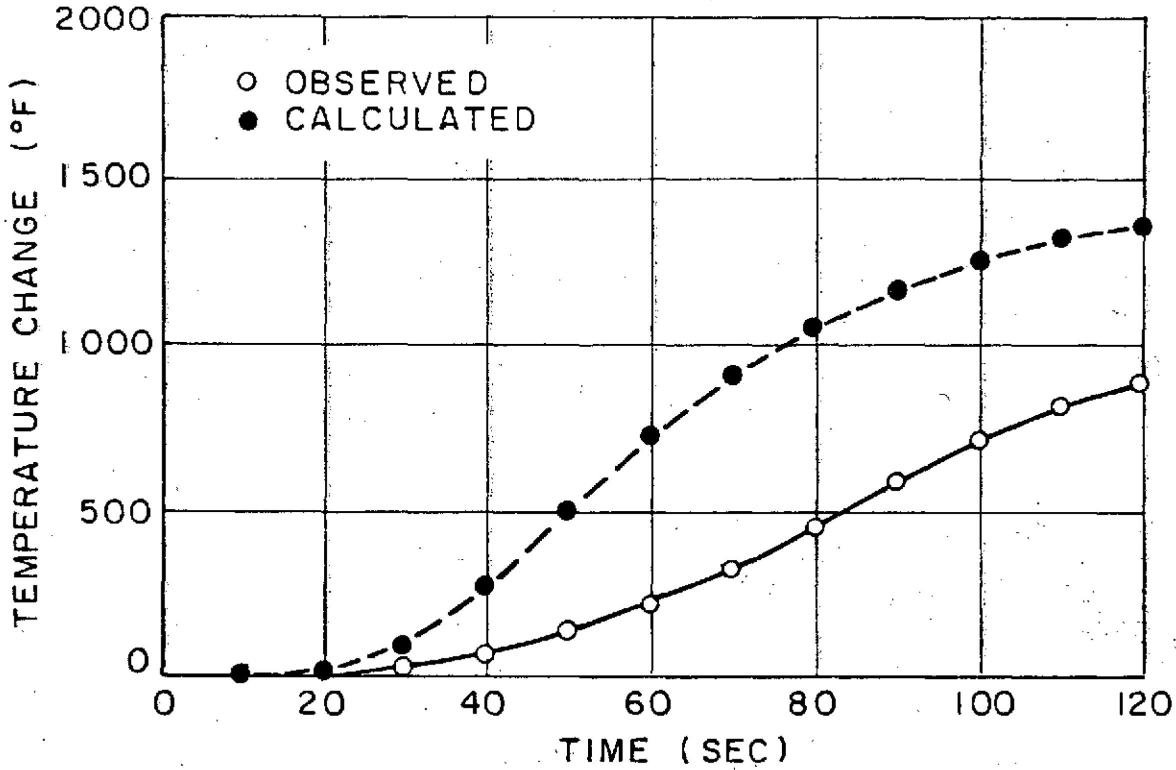
Note: —O—, Curve Observed from Experiment 2

FIGURE 16 Calculated and Observed Temperature Changes at Thermocouple 1



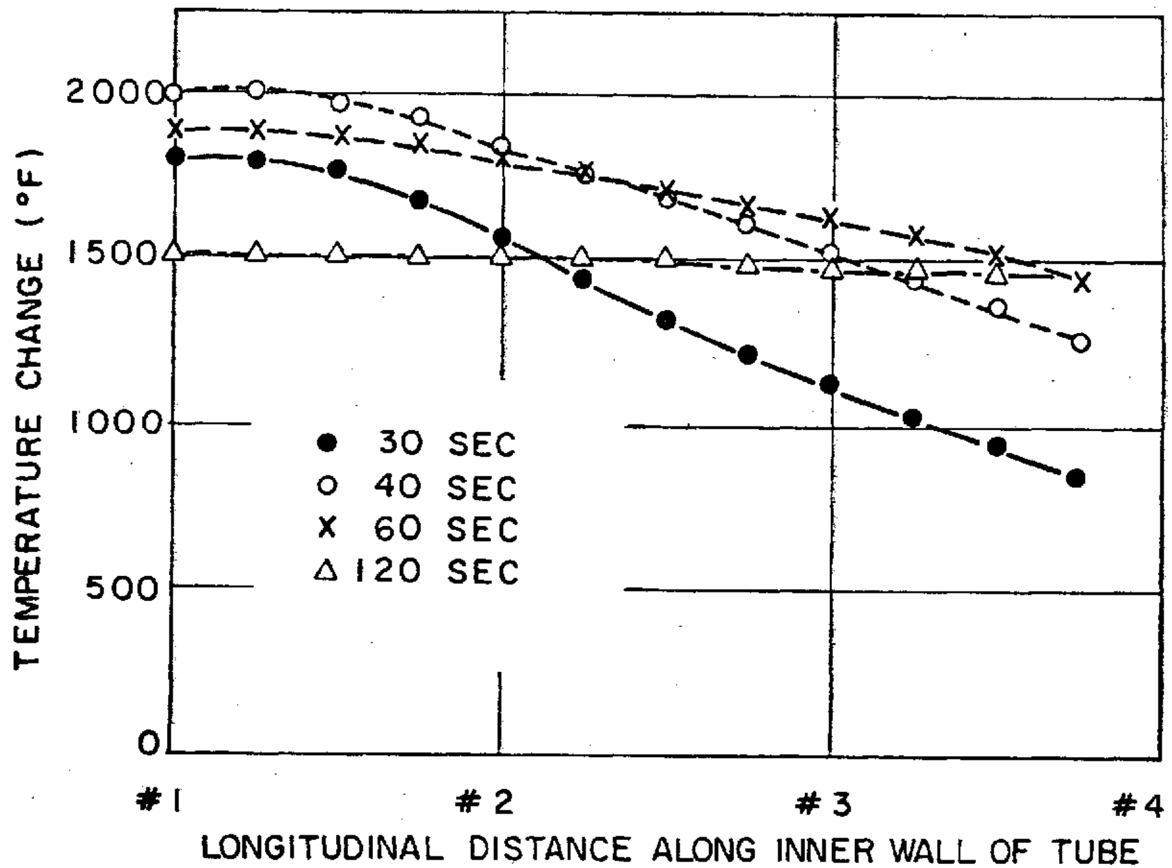
Note: —O—, Curve Observed from Experiment 2

FIGURE 17 Calculated and Observed Temperature Changes at Thermocouple 4



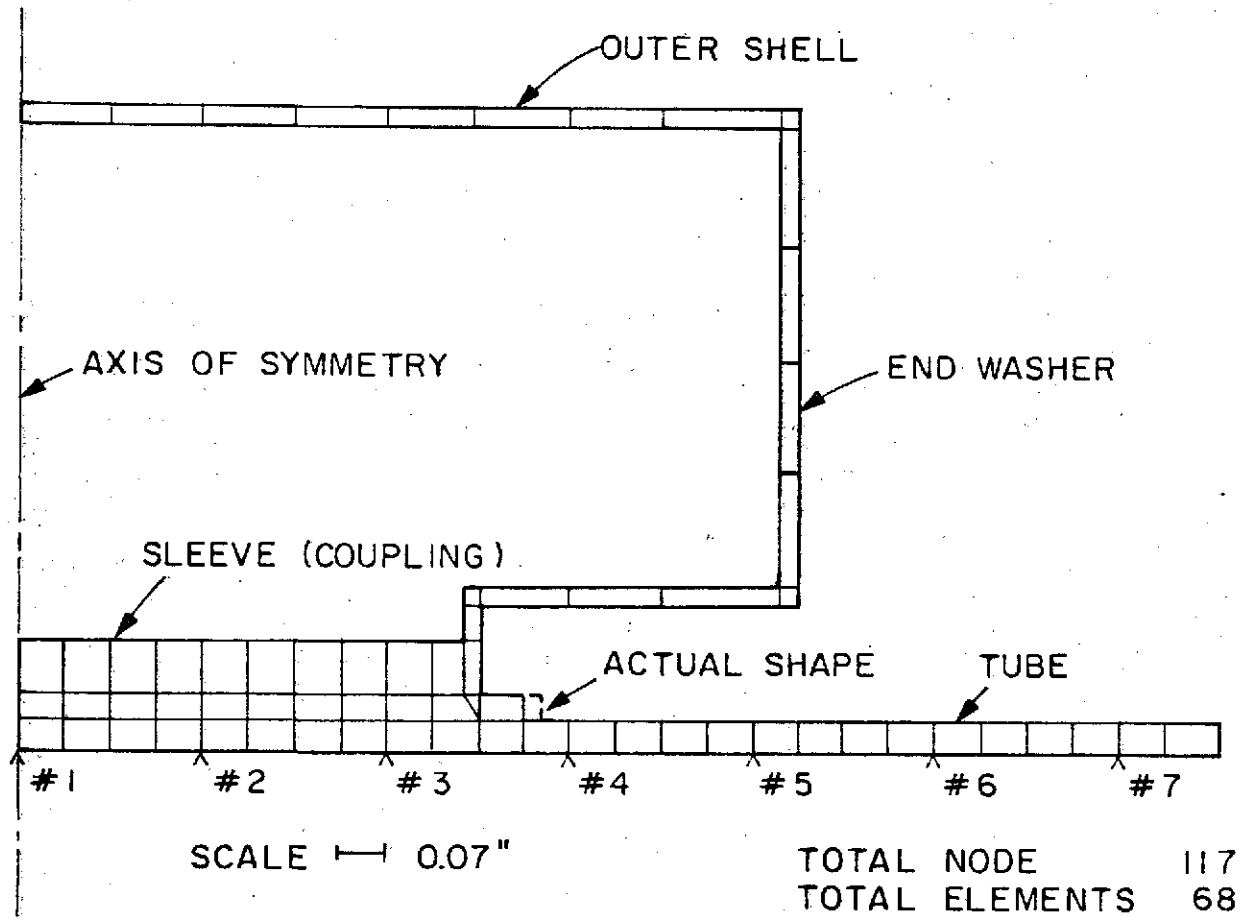
Note: —o—, Curve Observed from Experiment 2

FIGURE 18 Calculated and Observed Temperature Changes at Thermocouple 7



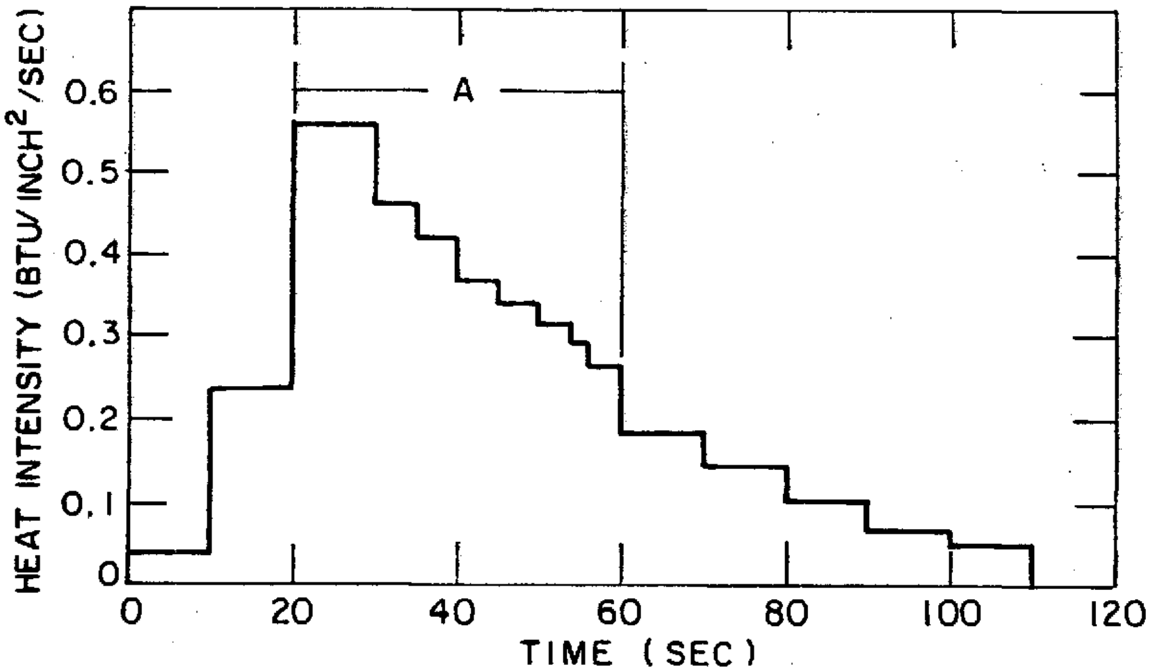
Note: #1, #2, #3, and #4 Correspond to These in Figure 15

FIGURE 19 Calculated Temperature Change Along Boundary Between Tube and Sleeve



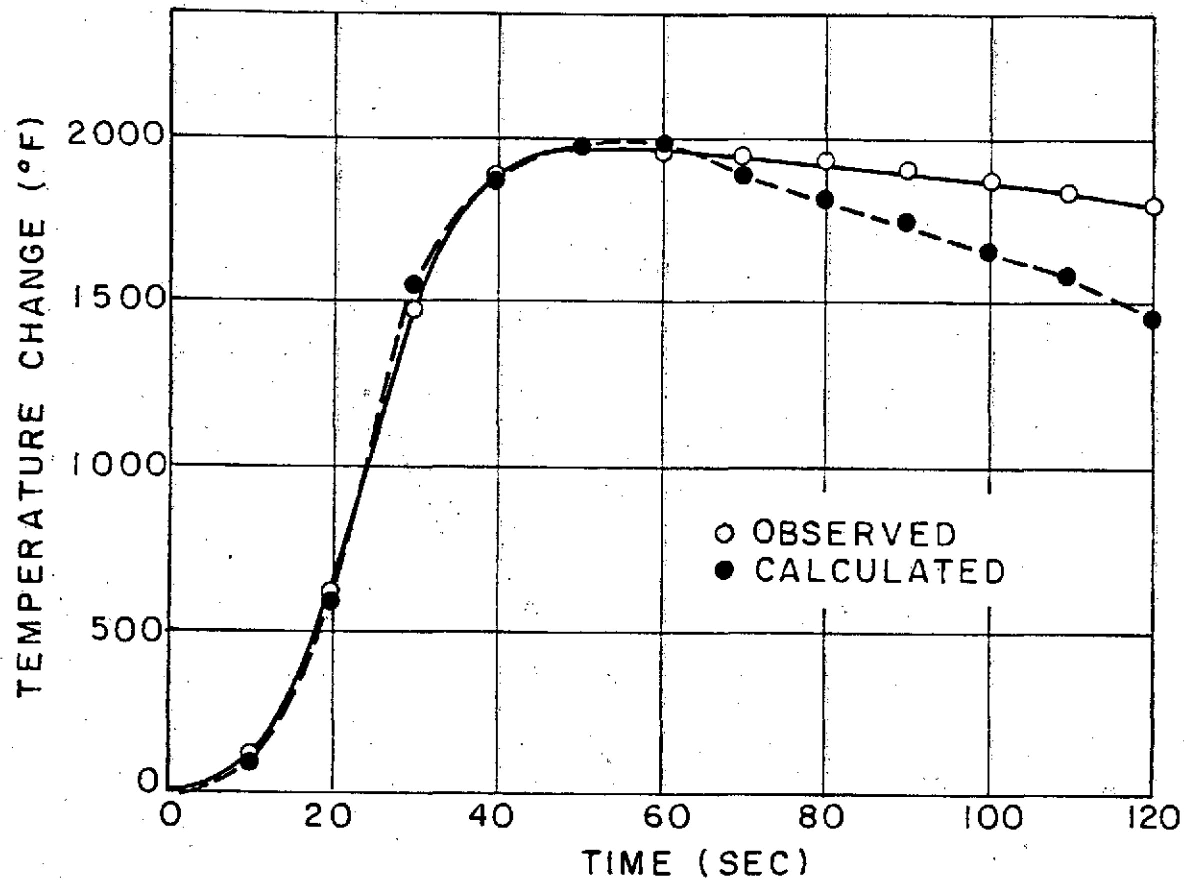
Note: #1 to #7 Denote the Locations of Thermocouples Used in Specimen No. 2

FIGURE 20 Mesh Pattern Used for Finite Element Analysis



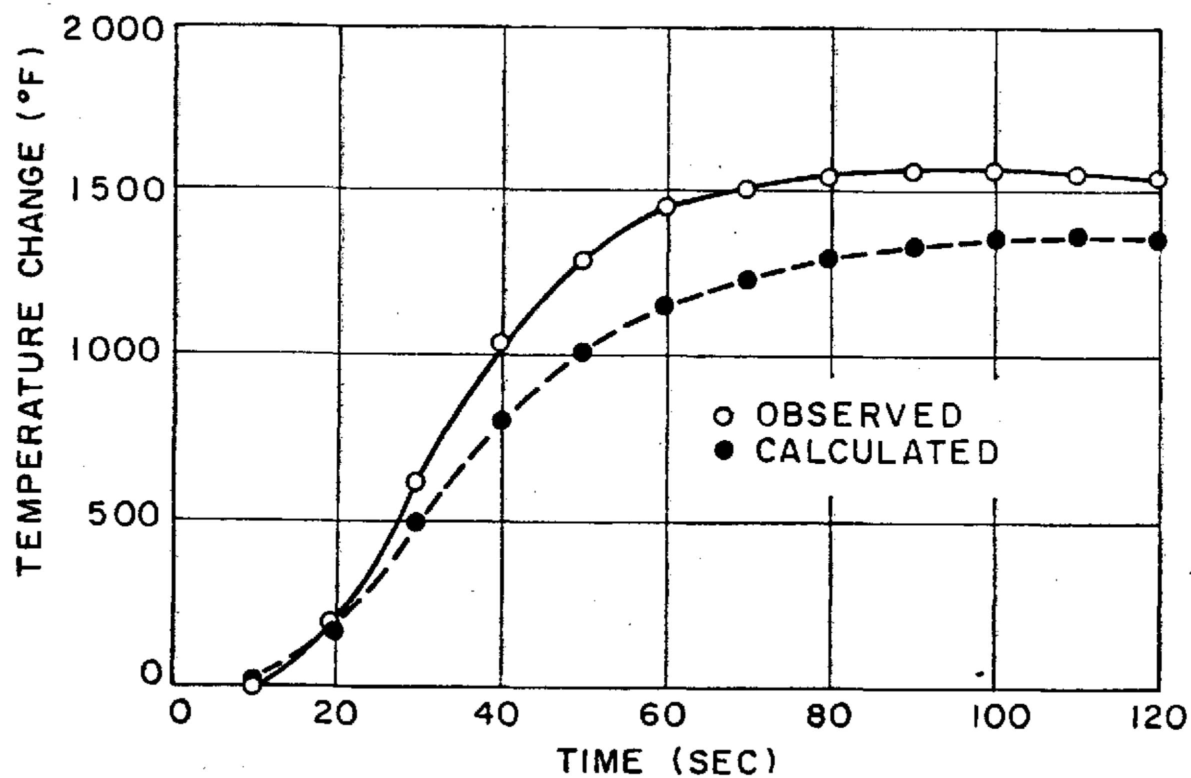
Note: A Denotes Type of Heat Distribution and the Remaining, Type C in Figure 14

FIGURE 21 Assumed Heat Intensity



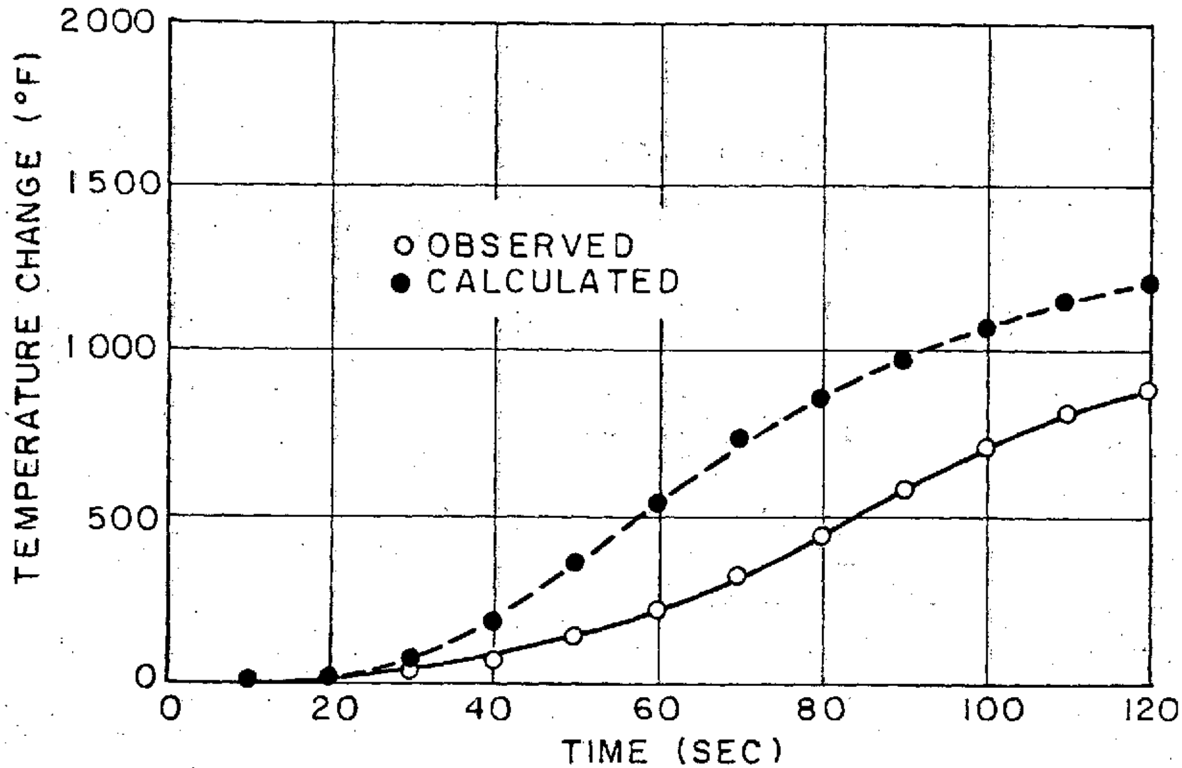
Note: —O—, Curve Observed from Experiment 2

FIGURE 22 Calculated and Observed Temperature Changes at Thermocouple 1



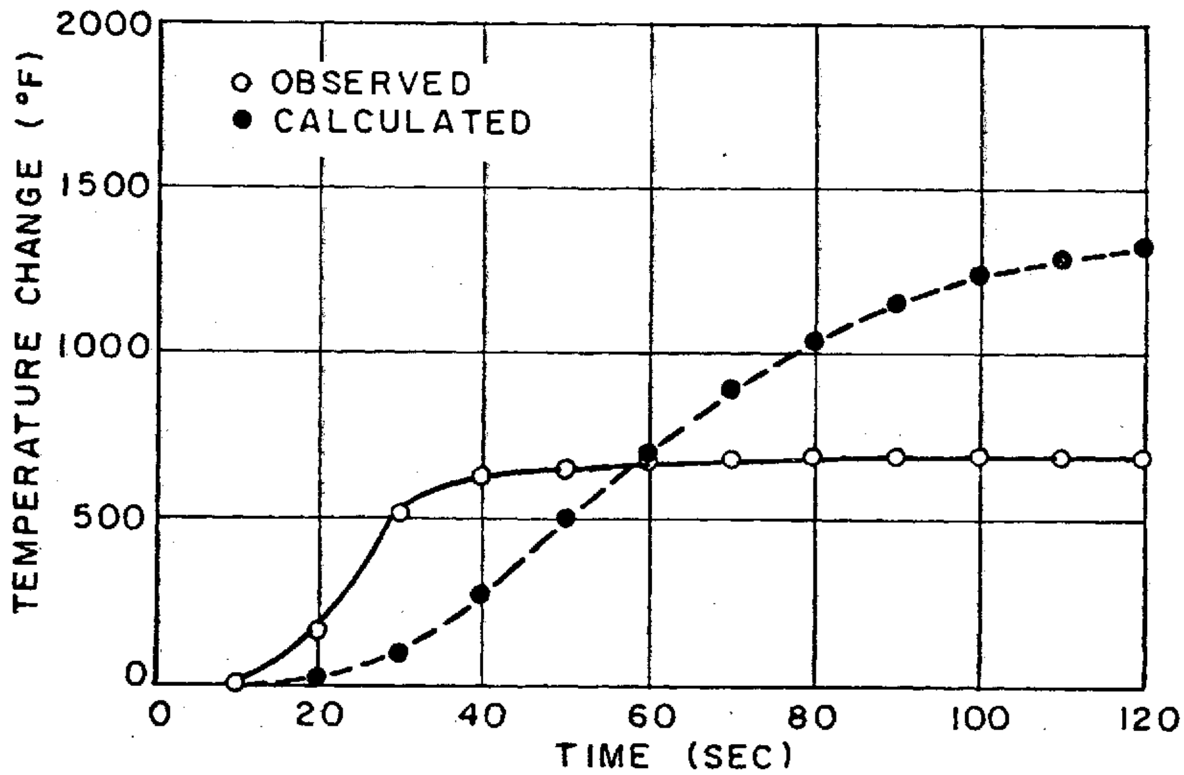
Note: —0—, Curve Observed from Experiment 2

FIGURE 23 Calculated and Observed Temperature Changes at Thermocouple 2



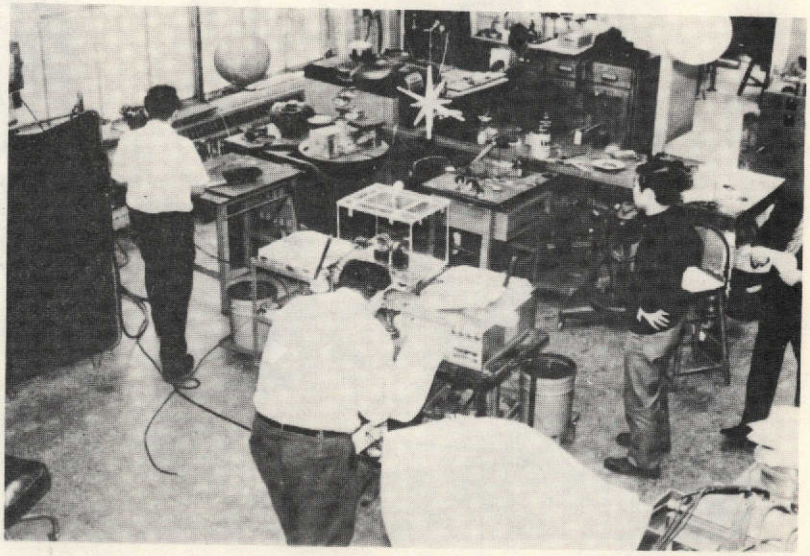
Note: —O—, Curve Observed from Experiment 2

FIGURE 24 Calculated and Observed Temperature Changes at Thermocouple 7

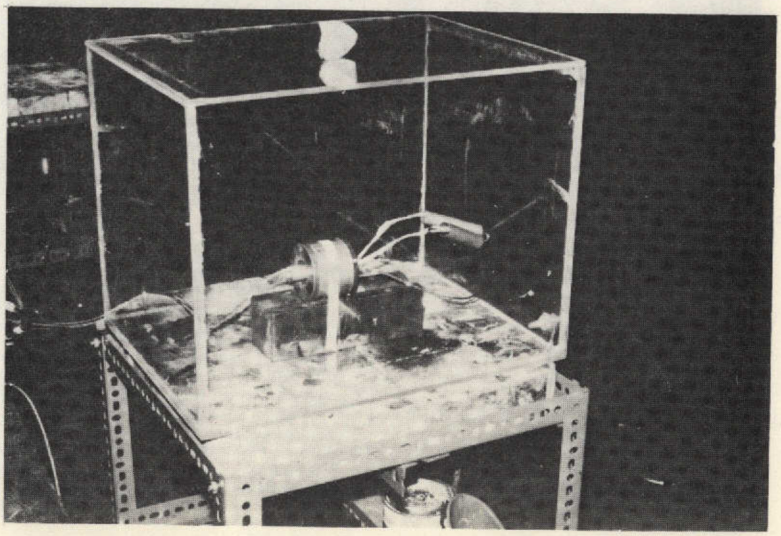


Note: —O—, Curve Observed from Experiment 2

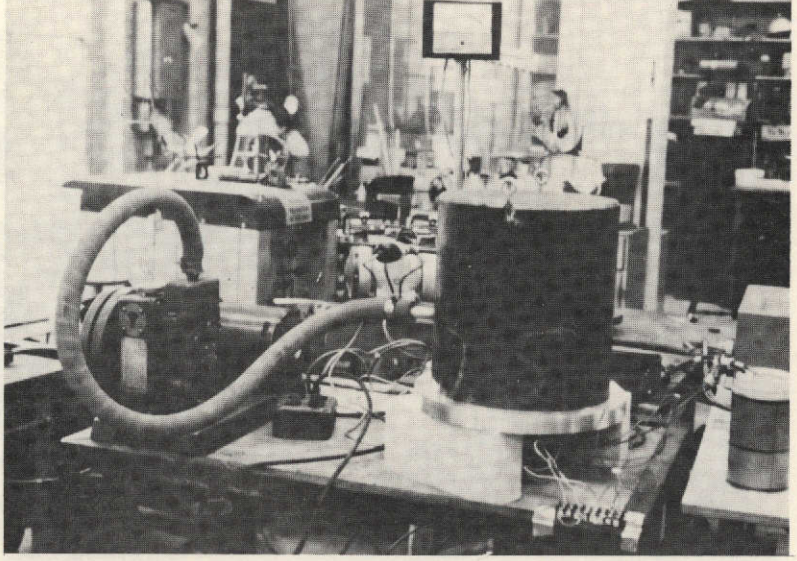
FIGURE 25 Calculated and Observed Temperature Changes at Thermocouple 8



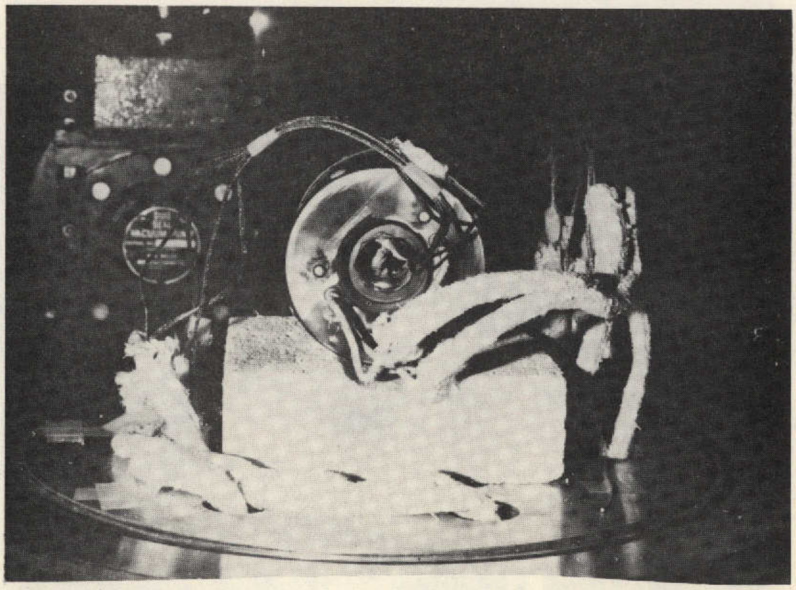
PHOTOGRAPH 1 Laboratory Set-up for Experiment 2



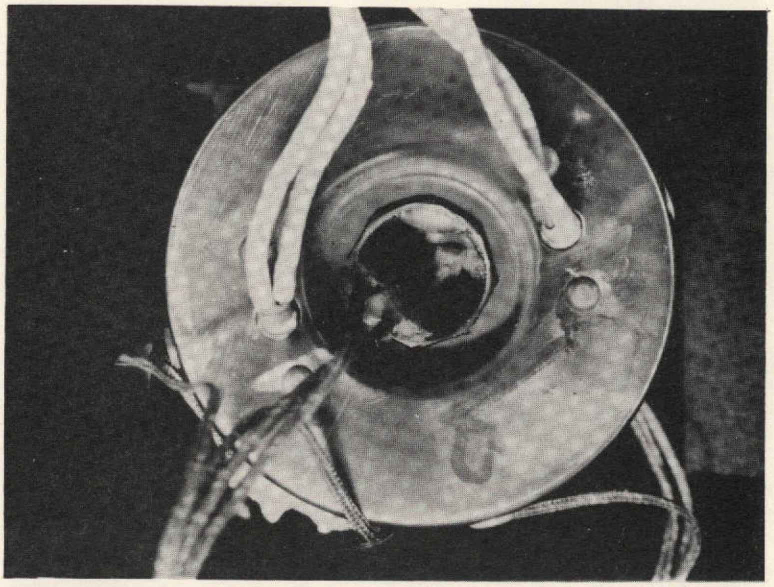
PHOTOGRAPH 2 Specimen Set in Plexiglas Box



PHOTOGRAPH 3 Laboratory Set-up for Experiment 3



PHOTOGRAPH 4 Specimen Set on Circular Disc



PHOTOGRAPH 5 Appearance of Melting of Brazing Alloy After Experiment

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